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POTENTIAL ENVIRONMENTAL IMPACTS OF SOLAR HEATING AND COOLING SYSTEMS

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Bethesda, Maryland

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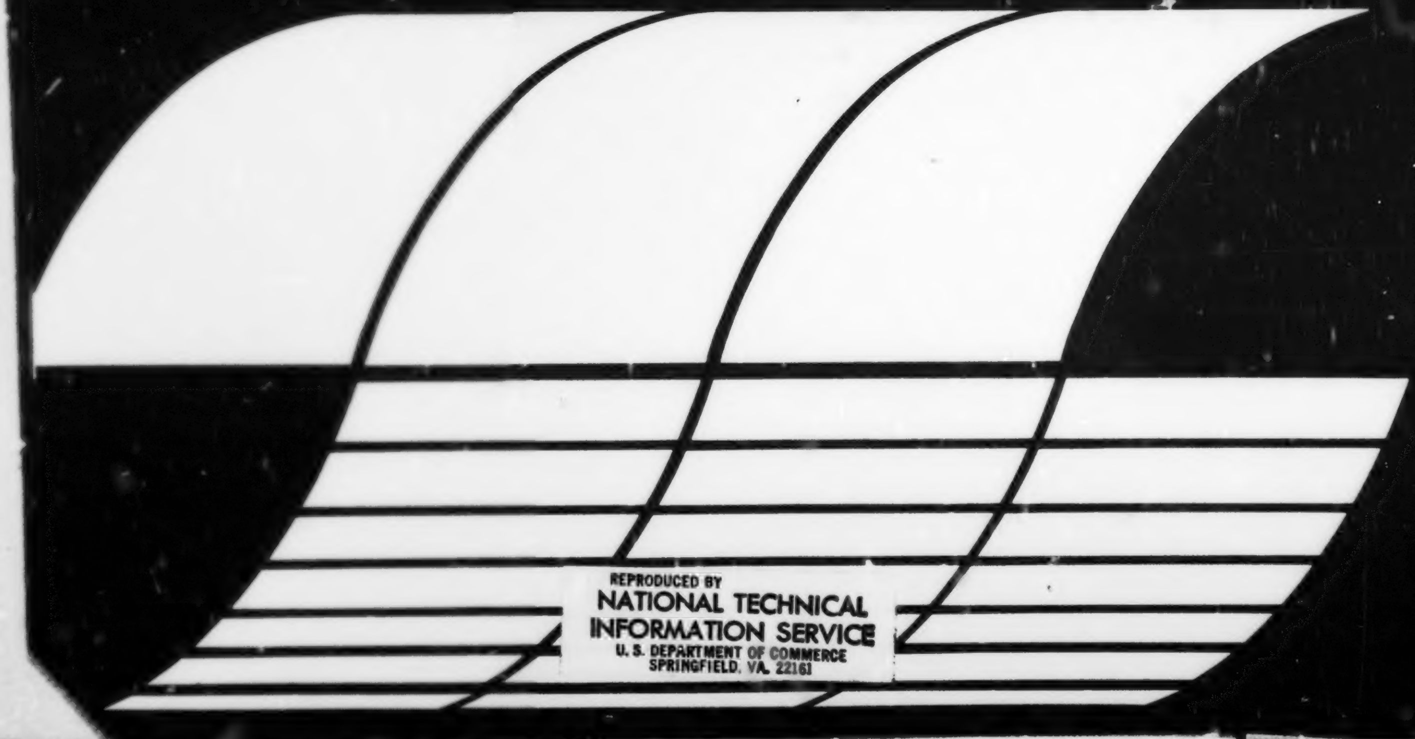

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The subject of this report is the potential environmental consequences of solar energy utilization for heating and cooling buildings. The report contains three chapters. The first chapter identifies the areas in which both positive and negative impacts are possible. The second chapter summarizes the national research and development program directed toward solar heating and cooling technology and describes how these programs address environmental considerations within the context of Federal agency responsibilities. The third chapter contains a general methodology for estimating the impact on air pollution of solar energy utilization in urban areas, and also contains an example application of the methodology.

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PREFACE

The subject of this report is the potential environmental consequences of solar energy utilization for heating and cooling buildings. The report does not address other solar technologies such as solar electric/direct conversion or biomass conversion. This analysis was undertaken for four reasons:

- To provide a general but comprehensive evaluation of the environmental tradeoffs between solar energy and fossil fuel utilization

- To encourage the development of solar energy technologies which are environmentally acceptable

- To assist in the coordination of Federal agency activities related to the environmental impacts of solar heating and cooling systems

- To develop a methodology for quantifying the potential air pollution impacts of solar energy systems resulting from the displacement of fossil fuel combustion, which can serve as a technological option for controlling environmental pollution.

The report contains three chapters. The first chapter identifies the areas in which both positive and negative impacts are possible. The second chapter summarizes the national research and development program directed toward solar heating and cooling technology and describes how these programs address environmental considerations within the context of Federal agency responsibilities. The third chapter contains a general methodology for estimating the impact on air pollution of solar energy utilization in urban areas, and also contains an example application of the methodology.

The identification of potential environmental effects of solar heating and cooling systems, given in Chapter I, includes a discussion of the increases and decreases in air, water, and solid waste residuals associated with these systems. In addition, other impacts which are more qualitative but no less concrete in nature, including aesthetic, social, and consumer safety considerations, are also identified. These qualitative impacts are addressed because, in many respects, the manner in which this energy resource is tapped differs radically from conventional energy forms, and implies many novel problems.

The second chapter of the report contains five sections. In the first two sections the role of R&D for solar heating and cooling is described in the context of the national energy R&D plan, and the responsibilities of key Federal agencies and departments involved are identified. The third section describes planned solar heating and cooling demonstration projects. Because a large number of buildings in many geographic regions will be involved, these demonstrations will probably direct attention to the first environmental impacts of any magnitude associated with solar energy applications. The fourth section summarizes EPA's role in the development of solar technologies. The last section of the chapter identifies the Federal agencies which are responsible for analyzing and mitigating the potential environmental impacts of solar systems which were discussed in Chapter I.

The third chapter of the report describes a methodology for assessing the impact of solar heating and cooling systems in urban areas. Mathematical relationships are developed for projecting fuel savings in any urban area, as a function of the rate of acceptance of solar systems. The changes in emissions and ambient air quality resulting from solar-induced fuel savings are then discussed. Finally, a sample application of the methodology and a parametric analysis of regional emission savings using actual urban fuel use and building data are given.

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I. POTENTIAL ENVIRONMENTAL IMPACTS OF SOLAR HEATING AND COOLING SYSTEMS

Solar energy is often thought of as a source of energy for the future that will have purely beneficial impacts upon the environment. This is because the utilization of solar energy will result in conservation of fossil fuels. Decreased levels of fossil fuel combustion will result in a decrease in pollution released to the environment. In addition, conservation of domestic fossil fuels by solar energy will reduce the environmental impacts associated with the extraction, processing, conversion to usable form, and transportation of fossil fuels.

Solar energy is not a completely pollution-free source of energy, however. Although solar energy heating and cooling systems will not be direct sources of significant air or water pollution, many potential negative environmental impacts are associated with their widespread utilization. The most important of these environmental impacts are not directly associated with the operation of the equipment but rather with the production of materials for solar systems. The development of a solar energy industry that will supply a significant portion of national energy requirements by the turn of the century will entail the diversion of large quantities of materials, such as glass and copper, for the manufacturer of solar system components. The pollutants generated in the extraction and production of these materials must be considered environmental impacts of solar energy utilization.

In addition to air, water, and solid waste pollution, other environmental effects must be considered which are more subjective in nature. These environmental considerations include:

- Land use patterns for solar energy collection
- Thermal effects on local meteorology
- Toxicity and flammability of solar system working fluids and materials
- Consumer safety implications
- Impact on population distribution.

In order to assess the net environmental impacts of solar heating and cooling systems, positive impacts must be compared to negative impacts. This has not been attempted in a quantitative sense in this chapter. However, the discussion presented below indicates that it will be possible to control and to minimize most of the potential negative impacts of solar energy, as long as potential environmental problems are identified and corrected early in the development of the technology. The discussion also indicates that the serious negative impacts, such as the air pollution generated in the production of materials for solar systems, will be greatly offset by positive impacts, such as the reduction in air pollution due to a lower rate of fossil fuel combustion.

The discussion of the environmental impacts of solar energy systems is presented in this chapter in three sections:

- Expected Market Penetration of Solar Heating and Cooling Systems
- Air, Water, and Solid Waste Impacts
- Other Related Environmental Impacts.

1. EXPECTED MARKET PENETRATION OF SOLAR HEATING AND COOLING SYSTEMS

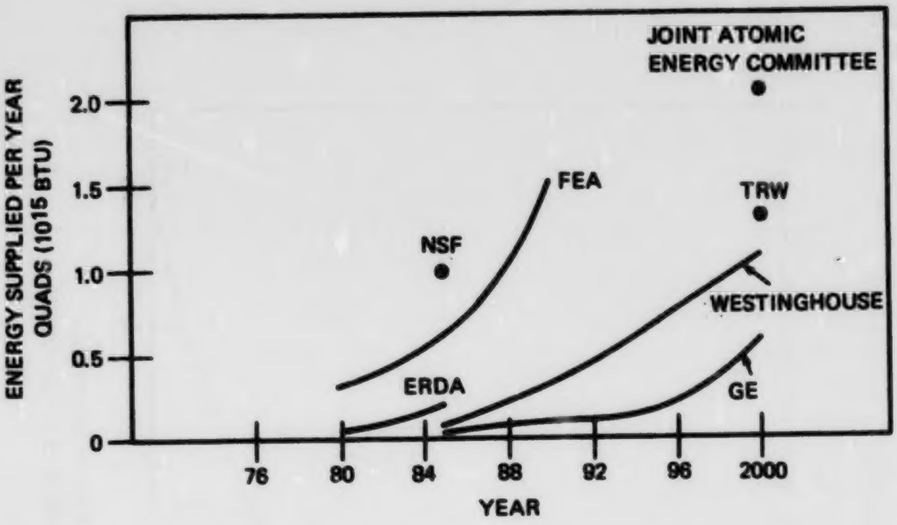
The rate at which solar heating and cooling systems will gain market acceptance will depend on several factors:

- The initial cost of solar equipment, including availability of capital, development of manufacturing capacity, and economic incentives
- The cost and availability of competing fuels, which may reflect future changes in rate structures
- Public attitudes and confidence
- Institutional and legal considerations.

Many of these factors will vary on a regional basis. The cost and optimum size of a solar system will be a function of climate and geography. The rate structures and availability of conventional fuels is distinctly regional, as are public attitudes and institutional/legal barriers. Several projections of market penetration are illustrated in Figure 1. Two forecasts of the total number of solar-equipped buildings are given in Figure 2.

FIGURE 1

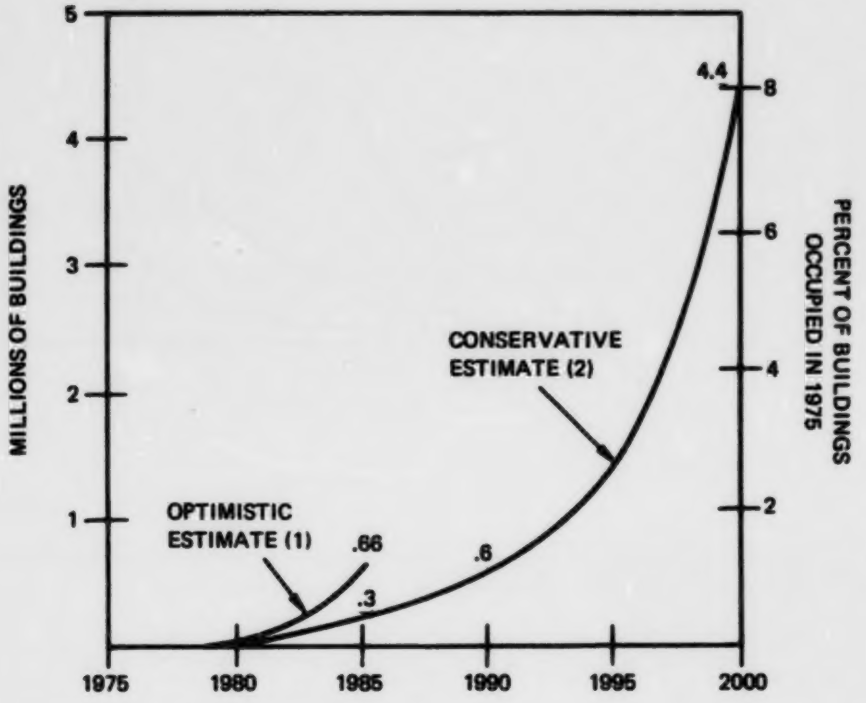
Energy Supplied By Solar Heating and Cooling Systems



References:

1. Westinghouse Electric Corporation, *Solar Heating and Cooling of Buildings*, Phase "O" Report, prepared for National Science Foundation, May 1974.
2. TRW Systems Group, *Solar Heating and Cooling of Buildings*, Phase "O" Report, prepared for National Science Foundation, May 1974.
3. General Electric, *Solar Heating and Cooling of Buildings*, Phase "O" Report, prepared for National Science Foundation, May 1974.
4. ERDA, *National Plan for Solar Heating and Cooling* (ERDA-23A), Oct. 1975.
5. FEA, *Project Independence Report*, November 1974.
6. Joint Committee on Atomic Energy, *Understanding the National Energy Dilemma*, 1973.
7. NSF, as cited in "But Not Soon," by Michael Harwood, *The New York Times Magazine*, March 16, 1975.

FIGURE 2
Solar Equipped Buildings
(Cumulative)



Sources:

1. ERDA, *National Plan for Solar Heating and Cooling* (ERDA-23A), Oct. 1975.

2. General Electric, *Solar Heating and Cooling of Buildings*, Phase "O" Report, prepared for National Science Foundation, May 1974.

Several forecasts have been developed concerning the respective share of the market for residential and commercial buildings, and for new and retrofit installations. ERDA's projections to 1985 are summarized in Figure 3.* Single family residences and multi-family low rise dwellings are the leading residential candidates; schools will be a major commercial application.† It can be seen from the figure that by 1985, commercial solar installations will likely supply about as much energy as residential solar systems, and that solar systems will tend to be incorporated into new buildings rather than retrofit into existing structures.

In summary, several estimates have been made for the amount and time frame of the potential energy savings resulting from solar heating and cooling systems. However, the estimates predict energy savings which are significant. In this case environmental impacts will be significant also. Consequently in the next sections potential environmental impacts are identified and discussed.

2. AIR, WATER, AND SOLID WASTE IMPACTS

The environmental impacts of solar energy utilization include the positive impacts associated with a reduced demand for fossil fuels, and the negative impacts associated with the production and operation of solar equipment. A comprehensive environmental assessment of each of these energy technologies must address the complete energy "system" for each technology. The energy system includes the extraction, production, distribution, consumption, and disposal of all materials, equipment, and fuels associated with each energy supply technology.

The potential environmental impacts of solar heating and cooling systems, both positive and negative, are summarized in Table 1. For each type of activity, the pollutant media which may be affected are identified. These environmental impacts are discussed in more detail below in the four sections:

- Reduction in Emissions Due to Reduced Fuel Combustion
- Increases in Emissions From Production of Materials

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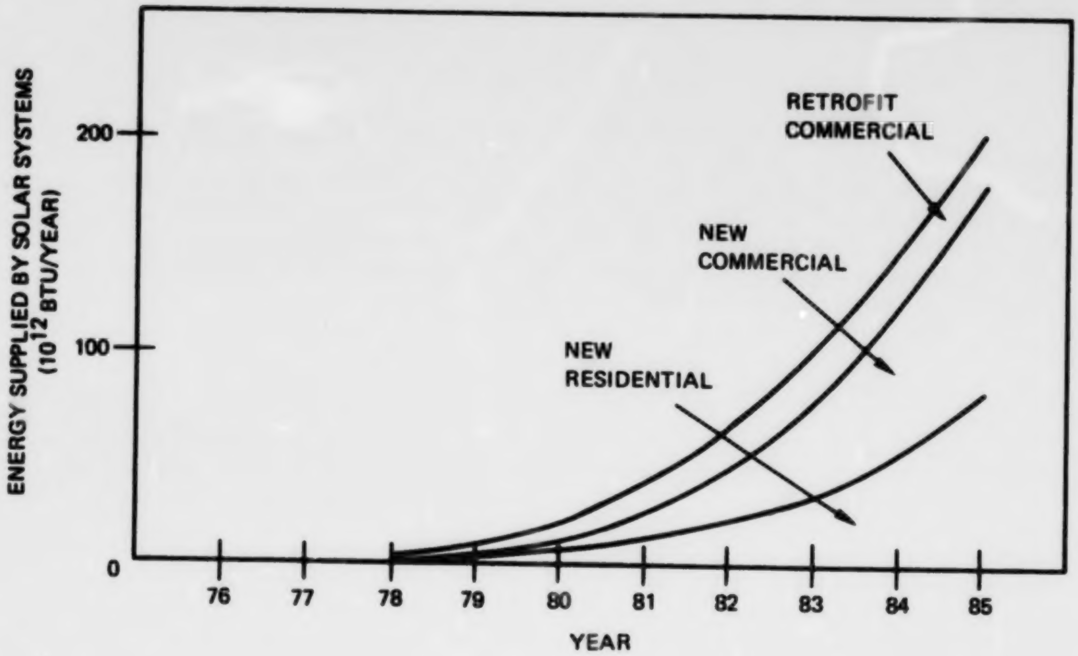
* ERDA, National Plan For Solar Heating and Cooling, (ERDA 23A), October 1975.

† TRW Systems Group, Solar Heating and Cooling of Buildings, Phase "0" Report, prepared for National Science Foundation, May 1974 (hereafter cited as TRW Phase "0" Report.)

FIGURE 3
Energy Supplied By Solar Heating and Cooling Systems By Building Type



Source:

ERDA, *National Plan for Solar Heating and Cooling* (ERDA-23A), Oct. 1975.

Table 1
Potential Environmental Impacts of Solar Heating and Cooling Systems

Environmental Impacts	Pollution Type		
	Air	Water	Solid
Positive Impacts			
• Reduced demand for fossil fuels for electricity generation and on-site combustion results in reduced:			
- Extraction of fuels and materials	●	●	●
- Processing of fuels and materials	●	●	●
- Fabrication of equipment	●	●	
- Transportation of equipment and fuels	●	●	
- Combustion of fuels and operation of equipment	●	●	
- Disposal of combustion by-products and used equipment			●
Negative Impacts			
• Increased production of solar systems results in increased:			
- Extraction of materials	●	●	●
- Processing of materials	●	●	●
- Fabrication of equipment	●	●	●
• Operation of equipment			
• Disposal of used solar system working fluids and components		●	●

- Water Quality Impacts
- Solid Waste Disposal.

(1) Reduction in Emissions Due to Reduced Fuel Combustion

As a result of the development of solar heating and cooling in the residential and commercial sectors, air pollution emissions will decrease because of reduced fuel combustion for heating and cooling buildings and providing domestic hot water, and reduced fuel combustion for electric power generation. The extent to which this fuel savings will be shared by on-site fuel combustion and electric generation will vary substantially from region to region, and will depend on a variety of factors including the cost and availability of competing fuels.

When solar energy use results in decreases in oil and natural gas combustion in solar-equipped buildings, the primary emission reduction will occur in the vicinity of those buildings. The reduction in pollution associated with decreased demand for electricity will not necessarily occur in the vicinity of the buildings using solar systems. Rather the emission reduction in an urban area will reflect the extent of solar utilization in the region as a whole.

In the future, the use of solar energy will most likely displace coal and oil use for generating electricity in central power plants, rather than oil or natural gas use in residential or commercial buildings. This is because the majority of solar systems will be installed in new buildings rather than in existing buildings, (see Figure 3 previously), and because electricity provides the largest share of the space conditioning and hot water requirements of new buildings. Thus in most situations, reduced air pollution will be due to reduced load requirements at central power plants, rather than reduced pollution at the buildings for which heating and cooling are required.

The conversion and transmission efficiency of most conventional power plants is on the order of 30 to 35 percent. Thus, the fuel and pollution savings per Btu provided by a solar system can be approximately three times greater when electricity is displaced than the savings per Btu associated with on-site fuel combustion. This is in spite of the fact that, in general, fuels are burned more efficiently at a power plant than in individual buildings, and pollution control devices are more applicable to power plants than to furnaces of individual buildings. An economic analysis examining the costs of solar heating and cooling systems versus retrofit control technology for existing power plants, and for solar systems versus new power plant construction would provide a clearer definition of the tradeoffs involved.

For the case of central plant emissions, two distinct time frames must be considered for the potential environmental benefits of solar systems:

- Near-intermediate term (limited market penetration)
- Intermediate-long term (widespread market penetration).

That is, the amount and type of power plant fuel combustion and pollution reduction will depend upon the type of load reduction resulting from use of solar energy. These two cases are summarized below. A more detailed discussion of how solar energy utilization may affect electricity generation at power plants is given in Chapter III.

- Near-intermediate Term

  The use of solar energy during periods of peak electricity demand will reduce pollution from peaking units, such as gas turbines or diesel units, while off-peak use of solar energy will reduce pollution from base load units. Clearly, the implications for regions and urban areas with high coal use are significant. Further research is warranted to examine the potential of solar heating and cooling as a technological option for reducing air pollution in Air Quality Maintenance Areas.

  Table 2 contains an estimate of the potential fuel savings in 1985 due to solar heating and cooling systems installed at that time. This estimate is based on the most optimistic forecast of energy savings (0.94 quad/year) given previously in Figure 1. The fuel savings shown in the table are based on the assumption that solar systems will displace

Table 2
Reduction in Fuel Use of 0.94 Quads*
Due to Solar Heating and Cooling Systems

If All Fuel Savings Are:	Resulting Fuel Savings	Percent of Total 1985 Fuel Use
Oil at point of use	150 million bbl	2.4
Natural gas at point of use	940 x 10^9 cu ft	3.2
Oil for electricity	450 million bbl	8.0
Natural gas for electricity	2820 x 10^9 cu ft	10.8
Coal for electricity	108 million tons	9.4

Sources:

- U.S. total energy consumption in 1985 will be 102.9 quads:
  FEA, *Project Independence Report*, November 1974 ($11 per barrel scenario).
- Fuel consumption data for 1985:
  The Commission on Critical Choices for Americans, *Energy: A Plan for Action*, April 1975.
- It is assumed that the thermal conversion/transmission efficiency for power plants in 1985 will be approximately 33%.

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*NSF, as cited in "But Not Soon," by Michael Harwood, *The New York Times Magazine*, March 16, 1975.

only one fuel. In reality, of course, savings will be shared by all the fuels shown in the table. If it is further assumed that emissions will decrease in proportion to fuel savings, then according to the table, in 1985 emissions from coal combustion could be reduced by as much as 9.4 percent of what they would be without solar systems.

Intermediate-Long Term

Long term potential coal savings and emission reductions on a nationwide basis are illustrated in Figures 4 and 5 respectively. In both figures conservative and optimistic estimates are given; these estimates reflect the assumption that all fuel savings due to solar heating and cooling systems will be in the form of coal burned to produce electricity. It can be seen from the figures that by the year 2000 the use of solar heating and cooling systems may produce significant nationwide coal savings (up to 13.3 percent) and emission reductions.

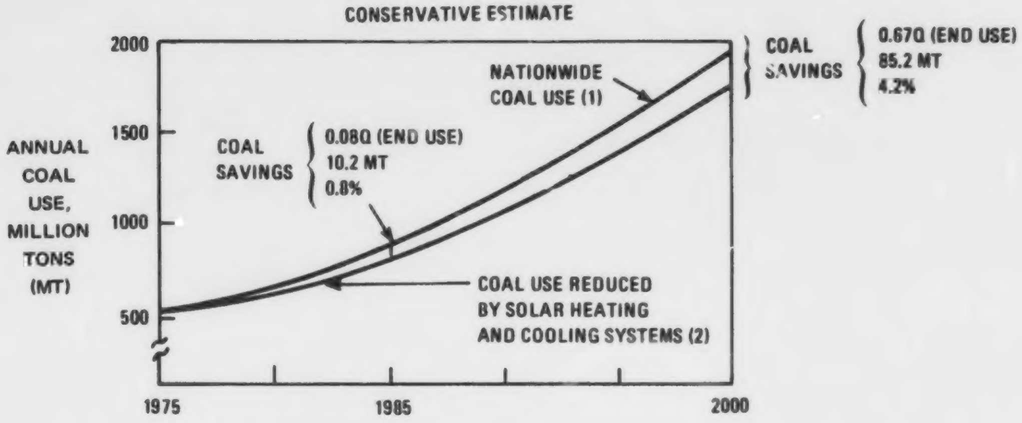
Widespread use of solar energy may also cause a curtailment in the rate of construction of new power plants, thus limiting the growth of new sources of air emissions. Utilization of solar systems in certain high population areas may conceivably alleviate the need for new fossil plants in remote locations.

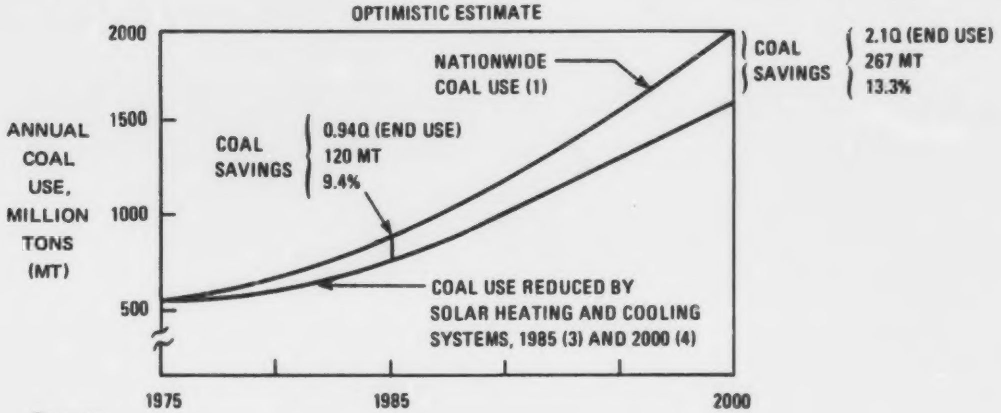
Conservation of fossil fuels will result in a decrease in emissions during the extraction, storage, processing and transportation of those fuels. For example, air pollution emissions occur during the mining and cleaning of coal, and during transportation of the coal (both from handling and from fuels burned to carry the coal). Thus solar energy utilization has the potential for reducing air pollution at all points in the fuel supply combustion and disposal cycle.

(2) Increase in Emissions From Production of Materials for Solar Systems

One of the most important impacts of the development of residential and commercial solar energy heating and cooling will result from the potentially large demand for materials for solar component production. Table 3 shows an estimate of the annual air pollution resulting from the production of glass, aluminum, and

FIGURE 4
Forecasts of Potential Coal Savings (If All Solar-Induced Fuel Savings Are Coal)


CONSERVATIVE ESTIMATE


OPTIMISTIC ESTIMATE

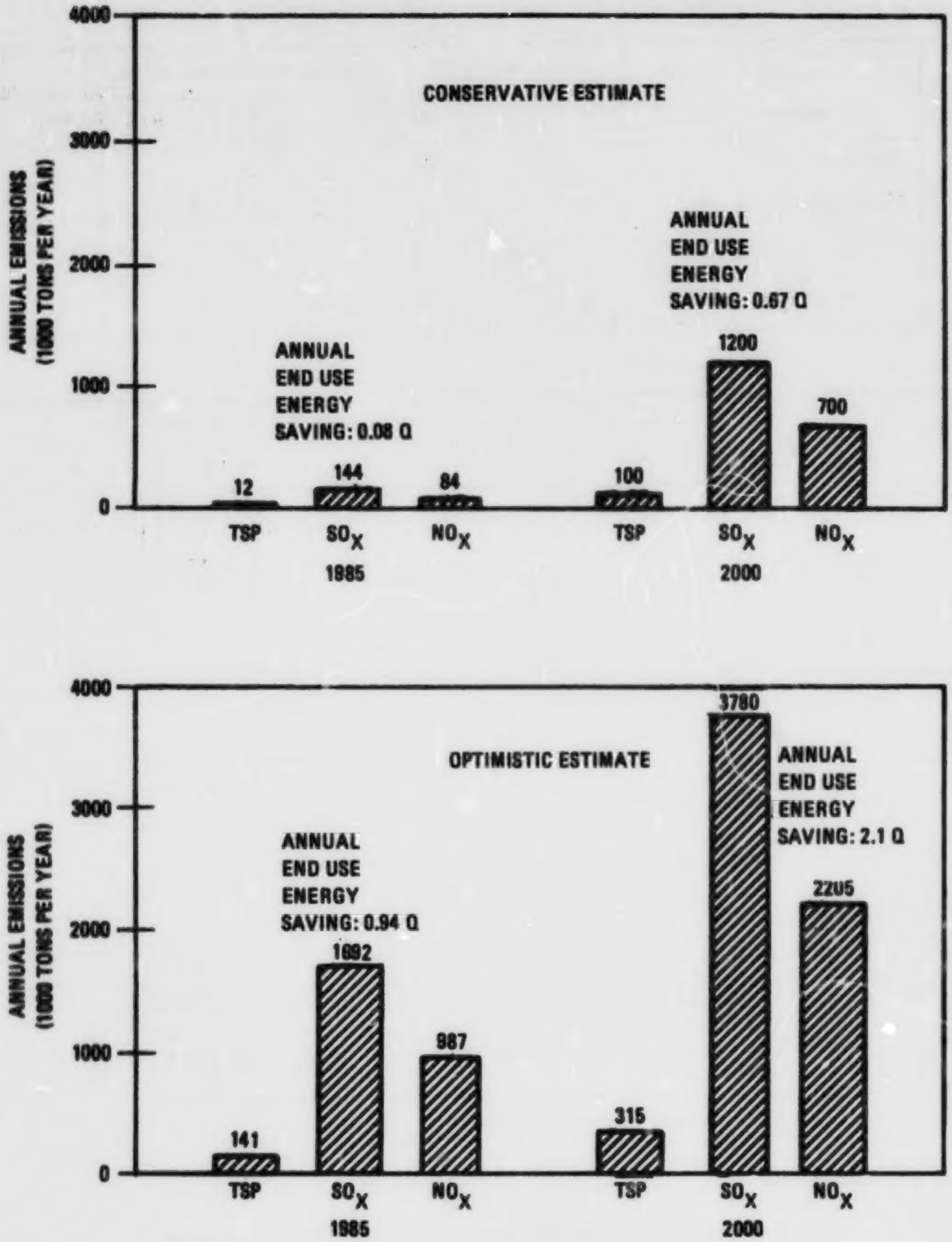
Sources:

1. The Commission on Critical Choices for Americans, *Energy: A Plan for Action*, April 1975.
2. General Electric, *Solar Heating and Cooling of Buildings*, Phase "O" Report, prepared for National Science Foundation, May 1974.
3. NSF, as cited in "But Not Soon," by Michael Harwood, *The New York Times Magazine*, March 16 1975.
4. Joint Committee on Atomic Energy, *Understanding the National Energy Dilemma*, 1973.

Assumptions:

1. All new residential and commercial buildings which will be equipped with solar systems would have used electricity for space conditioning which was generated from combustion of coal.
2. Conversion efficiency for electricity generation is 30% (33% thermal efficiency and 8% transmission loss).

FIGURE 5
Forecasts of Potential Emission Reductions (If All Solar-Induced Fuel Savings Are Coal)



SOURCES: FORECASTS OF ENERGY SAVINGS ARE FROM FIGURE 4
EMISSION FACTORS CORRESPOND TO FEDERAL NEW SOURCE PERFORMANCE STANDARDS

Table 3
Annual Criteria Emissions Associated With Solar Heating and Cooling Systems Providing 0.018 Quads Per Year

Material	Amount Required	Emissions Produced, Tons Per Year				
		TSP	SO_x	CO	HC	NO_x
Glass (soda-lime)	3.2×10^8 kg	330	–	–	–	–
Backing and heat exchange material (1)						
• If aluminum (heat controls, most common process) (2,3)	2.2×10^7 kg	530	1.0	29	1.6	10.0
• If copper, (controlled) (2)	7.2×10^7 kg	64	19,800	–	–	–

Material/Fuel	Amount Saved	Emissions Saved, Tons Per Year				
		TSP	SO_x	CO	HC	NO_x
Asphalt roofing	1.8×10^7 m^2	9.7	–	13.2	22	–
Fuel savings						
• If all savings are natural gas at point of use	5.1×10^8 m^3 (18×10^9 cu ft)	165	5.4	175	72	715
• If all savings are coal for electricity (4)	1.87×10^6 metric tons (2.1×10^6 tons)	2,700	32,340	1030	310	18,800

Sources:

The production levels and pollution data were taken from:
EPA, *Control of Environmental Impacts From Advanced Energy Sources,* March 1974.
Emission factors:
EPA, *Compilation of Air Pollutant Emission Factors,* April 1973.

Notes:

(1) Present indications are that copper will be used more than aluminum because it is more resistant to corrosion.
(2) Existing installations do not generally achieve this degree of control. However, these data refer to actual installations where controls have been evaluated.
(3) Includes emissions from a power plant burning natural gas to produce electricity for the electrolysis process.
(4) Emission factors for TSP, SO_x and NO_x correspond to Federal new source performance standards; conversion efficiency for power plants is 33%.

Assumptions:

Data reflect production of 300,000 solar systems per year, which will supply 75% of the annual space conditioning load of 80 MBtu per unit per year for 300,000 housing units. In other words, the 300,000 units will displace 18×10^{12} Btu (0.018 quads) of fuel annually. (Solar induced energy savings of 0.018 quads per year is estimated for 1985 in the EPA report referenced above.)

copper for solar system components (primarily collectors). The table also shows the annual emission reductions resulting from these solar systems, which include those due to fuel savings and to reduced demand for materials such as asphalt roofing (which will be replaced by solar collectors). The production and emission levels in the table were taken from a recent study of advanced energy systems sponsored by EPA.* The data developed in that study correspond to production and use of 300,000 solar systems per year, capable of providing 0.018 quads per year.

The fuel savings shown in the table are per year of operation, not cumulative. Solar systems manufactured from the materials shown in the table will cause air pollution reductions for many years after they are put into use.

With respect to the emission comparison given in Table 3, note that:

- The emission levels are based on assumptions concerning the extent of emission control for the manufacturing processes and power plant coal combustion.
- For a given urban area, most of the emission savings from buildings or power plants will occur in or near the urban area, while the emission increases at manufacturing facilities will occur in regions which may be located far away. Thus, a net increase in emissions due to manufacture of solar systems may occur near glass, aluminum or copper plants, with some degree of adverse environmental impact in their respective areas.
- The two fuels shown in Table 3 represent the least possible emission savings (natural gas consumed at the point of use) and greatest possible emission savings (coal for electricity). Actual annual emission savings, for a given urban area and for the nation as a whole, will probably be somewhere between the two.

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* EPA, Control of Environmental Impacts From Advanced Energy Sources, March 1974.

A comparison of positive and negative air pollution impacts over the full solar equipment lifetime is shown in Figure 6. The emission penalties (emissions produced) and emission savings are taken from the data in Table 3, modified to reflect levels of production of systems capable of saving 0.94 quads per year (the savings projected previously for 1985 [optimistic case] in Figure 4). The emission savings in Figure 6 are based on an equipment lifetime of 15 years. It can be seen from the figure that on a nationwide basis potential emission reductions over the full equipment lifetime more than offset emissions resulting from equipment production for all criteria air pollutants. As indicated above, the emission penalty associated with solar systems occurs only during manufacture of solar system materials and components, while the emission savings occur year after year during the equipment lifetime.

(3) Water Quality Impacts

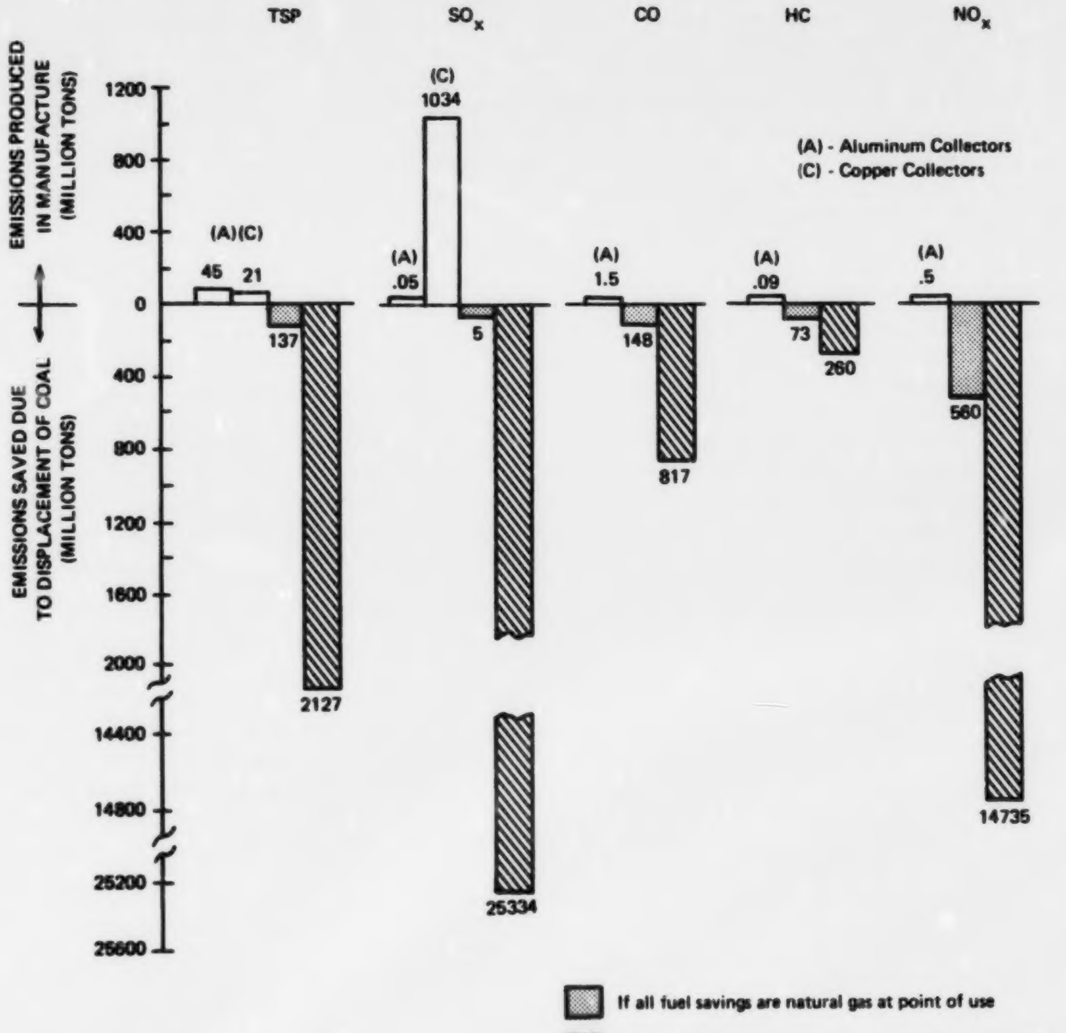
Utilization of solar heating and cooling systems may produce positive and negative water quality impacts. The positive impact will be a reduction in effluent discharge and thermal pollution from power plants due to the decrease in electricity demand. Power plant effluents usually include chlorine, which is used to minimize biofouling in the discharge system. This decrease in electricity demand may lead to reduced requirements for coal. The corresponding curtailment of mining operations will alleviate the demand on national water resources as well as reducing the area of mined lands which are non-point sources of water pollution.

The potential negative water quality impact is due to the disposal of solar system working fluids. Widespread use of solar systems will require the development of central collection facilities for disposal of degraded supplies of heat transfer fluids or antifreeze solutions. Disposal of waste fluids such as antifreeze is not a new problem but because these fluids are likely to be used by individual consumers in quantities that are quite large, considerable care must be taken to avoid potentially harmful dumping.

(4) Solid Waste Disposal

Two types of solid waste disposal problems may occur with solar energy systems: the solid waste

FIGURE 6
Comparison of Positive and
Negative Air Pollution Impacts
(15 Year Life-Cycle Basis)



Source: Emission data presented in Table 3; solar equipment lifetime assumed to be 15 years; system production levels correspond to annual energy savings of 0.94 quads per year (end use).

residuals associated with the production of system components, and the disposal of those components when they are no longer needed.

The solid waste residuals generated during the production of solar components include those from the extraction of raw materials, the refining of these materials, and the fabrication and assembly of components. The major materials of solar systems are glass, copper, and aluminum; there are solid waste residuals which are associated with the mining of metals and minerals, and the refining of these materials to produce the primary metals and glass. There are also solid waste residuals, primarily scrap wastes, from the fabrication and assembly of components.

The disposal of used solar system components should not present significant problems. It is important that, whenever possible, recyclable materials be used in the manufacture of solar systems so that environmental impacts of solar energy are not compounded by the production of unnecessary solar-related wastes. Furthermore, solar system specifications should encourage the use of materials which are plentiful so that environmentally costly extraction technologies are not encouraged. A recycling program should probably be considered an integral part of the commercialization of solar heating and cooling technology.

3. OTHER ENVIRONMENTAL IMPACTS

In addition to the air, water and solid waste residuals associated with solar systems which were discussed in the previous section, there are other environmental effects which are more subjective in nature. These potential impacts, which include aesthetic, social, and consumer safety considerations, are discussed in this section.

(1) Effect on Land Use Patterns

1. Zoning

The widespread use of solar energy will have a very visible impact on the manner in which land is utilized, since large quantities of land will be affected. Even for residential and commercial uses of solar energy for heating and cooling buildings, it may be necessary to set aside substantial land areas especially for solar collectors. Building spacing and building height must be planned carefully to maximize collector exposure to the sun. Thus, zoning laws will specify in more detail the type of development permissible on different parcels of land.

If rooftop collectors become widespread, zoning problems will be solved more easily if areas of land are zoned with respect to the minimum as well as the maximum height of buildings. The more uniform the height of buildings in a particular development, the fewer the problems with sunlight obstruction. Finally, proper spacing in the interface between zones reduces obstruction problems. Use of solar energy will, therefore, generally entail a less concentrated use of land than is the current practice in urban areas.

It will be necessary to review residential landscaping concepts in accordance with the need for maximum solar exposure. This will mean that the use of trees in close proximity to buildings may be curtailed. An energy-related effect of fewer trees is that natural cooling of buildings because of shading may be reduced. Solar systems which include heating but not cooling capabilities will be less seriously affected by the presence of trees close to the building. During much of the winter the trees will be bare, and in summer the trees will help reduce the conventional cooling load.

The issue of "sun rights" can be avoided with proper zoning and building orientation in the case of new developments. A body of legal precedent in this area may develop as a result of dispute over the right to sunshine of existing buildings. Widespread use of solar energy could place a limit upon the extent to which existing urban areas are further developed. For example, a doctrine in British common law known as the doctrine of "ancient lights"* limited the extent to which tall buildings were constructed in London. The establishment of a legal right to sunlight in American law could have a similar impact.

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* This common law doctrine defined the right of persons living or working near ground level to a sunlit environment.

2. Aesthetics and Building Orientation

Utilization of solar energy use could influence residential and commercial architectural styles. The design of collector configurations as integral parts of roofs and the use of concentrating surfaces could radically change building styles. These effects would probably be mitigated, however, because public tastes, especially in the case of single-family homes, have always been conservative and not very susceptable to rapid change. Building codes also discourage innovation to some extent. Similarly, the building industry is slow to adapt to new styles. Therefore, solar systems are likely at first to be incorporated into existing accepted building styles and any changes are likely to evolve slowly over many years.

(2) Thermal Effects on Local Meteorology

The impacts in terms of direct thermal pollution of the use of solar energy in residential and commercial space heating, hot water heating and space cooling applications will be minimal. Space heating and hot water heating systems are closed systems which do not reject heat to the external environment. Solar cooling systems involve heat rejection from the cooling tower as well as minor cooling water bleed off but these effects are not expected to have any significant impact on the environment.

Many cities have become "heat islands," partly because of the release of heat energy associated with many forms of human activity. In a similar way, the use of large areas of solar collectors in urban areas may influence weather conditions, since some of the sunlight that is normally reflected from buildings back into the atmosphere will be captured by the collectors. This may affect temperature gradients in the air, which are significant determinants of wind, cloud-cover, atmospheric mixing and, ultimately, air quality. There could be a feedback effect because increased cloud-cover will alter the effectiveness of solar collectors. Further study in this area is necessary to determine the potential extent of these impacts.

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* Research is now underway in this area sponsored by the Electric Power Research Institute as part of a study of the environmental impacts of solar thermal electricity generation.

Large collector networks can disturb the natural heat balance by reducing ground temperatures and thereby may impact plant and animal life. These potential impacts can be expected to be much more serious in the case of central station solar thermal electricity generation, where vast areas of land devoted to collection equipment may be required. Much more detailed research in this area is also required.

(3) Toxicity and Flammability of Solar System Fluids and Materials

Materials used in solar heating and cooling systems do not in general present a significant problem with respect to risk of accidental release of toxic materials. The components of solar collectors must be tested, however, to ensure that corrosion or erosion due to long exposure to the environment will not result in the release of potentially harmful substances. Since solar systems will be composed of materials already in common use, such as copper, aluminum, steel, and glass, no special problem in this area should be anticipated.

Working fluids must be carefully examined for similar impacts in case of accidental release from the system. In general, no major problems are currently foreseen by manufacturers of solar systems, although the flammability of certain substances which may be used in heat transfer and heat storage devices may present a problem. To date, researchers have limited development efforts in the area of heat transfer fluids and heat storage materials to substances with fairly low potential toxic effects. In addition, building code restrictions on the amount of ammonia that can be used inside a building will require that absorption cooling systems using ammonia as the refrigerant be located on the exterior. This will eliminate problems that could arise due to the moderate toxicity and potential flammability of ammonia. Table 4 summarizes possible environmental or health effects associated with heat transfer fluids, refrigerants, absorbents, corrosion inhibitors, wetting agents, and heat storage materials which are likely to be used in solar systems.

(4) Consumer Safety Implications

Certain characteristics of solar systems may present limited hazards to consumers and to the general

Table 4
Characteristics of Solar System Working Fluids

CHEMICAL SUBSTANCE	ADVANTAGES FOR SOLAR SYSTEM APPLICATION	DISADVANTAGES FOR SOLAR SYSTEM APPLICATION	TOXICITY	FLAMMABILITY
1. Heat Transfer Fluids				
• Dimethyl Siloxane Polymers (Dow Corning 200)	Low freezing pt.; high dielectric strength (use with dissimilar metals); high boiling pt.; thermal stability; good, viscosity-temperature characteristcs	Heat capacity about half that of water; although fluids with a wide range of viscosities are available, only fluids with viscosities of 50 centistokes or less can be centrifugally pumped below 40°F	Low toxicity, although temporary irritation caused by direct contact with the eyes	Low hazard; high flash points
• Aromatic Hydrocarbons (Monsanto Therminol Fluids e.g. Therminol 55, Therminol 60)	Low freezing pt. (60°F typical); high boiling pt. (600°F typical); thermal stability	Heat capacity about half that of water	Moderate; comnarable in toxicity to light mineral oil; toxic if ingested; mildly irritating if contacts eyes; vapors mildly irritating with prolonged exposure	Low hazard; flash points above 300°F
• Diethyl Benzene (Dowtherm J)	Low freezing pt. (-100°F); High boiling pt. (358°F); low viscostly; easy to pump; thermal stability	Lower heat capacity than water	Moderate; comparable in toxicity to kerosene; toxicity comparable to therminol fluids	Moderate hazard it in contact with a source of ignition; flash point: 145°F; fire point: 155°F
• Paraffinic Oil Mixtures (Dowtherm HP)	Very high boiling pt. (680°F)	Viscous at low temperatures; not suitable for use in cold climates; lower heat capacity than water	Low toxicity; a laxative; may cause aspiration pneumonia	Low hazard; flash pt. greater than 440°F
• Ethylene Glycol	High boiling pt. (356°F); low freezing pt. (8°F); used in solution with water, so higher heat capacity than above fluids	Higher freezing point than above fluids	Toxic if ingested; low toxicity otherwise	Slight hazard if in contact with a source of ignition; flash point: 232°F
• Fluorocarbons (e.g. Dupont Freons, such as Freon 113)	Low freezing points; thermal stability	Most freons have a low boiling point, therefore, to use these fluids some collector pressurization would be needed; lower heat capacity than water	Toxicity unknown but believed to be moderate	Very slight when exposed to heat or flame

Table 4
(Continued)

CHEMICAL SUBSTANCE	ADVANTAGES FOR SOLAR SYSTEM APPLICATION	DISADVANTAGES FOR SOLAR SYSTEM APPLICATION	TOXICITY	FLAMMABILITY
2. Solar System Heat Storage Materials				
• Salt Hydrates (e.g. Sodium Sulfate Decahydrate)	Far less volume and weight than water per btu stored; non-corrosive	Limited lifetime: currently, 2-3 years, research ongoing to improve this to 5-10 years	Materials that have been tested were chosen for low toxicity	Materials are non-flammable and non-combustible
• Paraffin Wax	Less volume per btu stored than water	Lower heat of fusion than salt hydrates; phase change in paraffins accompanied by 10% loss in volume	Low toxicity; minor irritation from prolonged exposure	Slight hazard; flash point: 390°F
• Diphenyl	Less volume per btu stored than water	Generally, a lower heat of fusion than salt hydrates	Moderate to high w.r.t. inhalation and ingestion	Slight hazard
• Diphenyl Oxide	Less volume per btu stored than water	Generally, a lower heat of fusion than salt hydrates	Moderate	Moderate hazard when exposed to heat or flame
3. Absorption Refrigeration Fluids				
• Lithium Bromide	Water/lithium bromide refrigerant/absorbent combination most comonly used in absorption cooling; conventional lithium bromide units can be derated to operate at temperatures supplied by solar collectors	Lithium bromide crystalizes if cooling unit operated too far below design capacity	No toxicity problem reported toxicity low in small quantities	No flammability hazard

Table 4
(Continued)

CHEMICAL SUBSTANCE	ADVANTAGES FOR SOLAR SYSTEM APPLICATION	DISADVANTAGES FOR SOLAR SYSTEM APPLICATION	TOXICITY	FLAMMABILITY
3. Absorption Refrigeration Fluids (Continued)				
• Ammonia	Ammonia/water refrigerant/absorbent combination does not have problem with freezeup during low-temperature operations	Ammonia/water systems operated at higher pressures than water/lithium bromide systems; cop found, generally, to be slightly lower	Moderate toxicity w.r.t irritation and inhalation; severe toxicity w.r.t. ingestion; vapor can cause skin burns	Slight hazard; when heated emits toxic fumes
• Lithium Chromat	Used in water/lithium bromide cooling systems as a corrosion inhibitor		High toxicity w.r.t. irritation, ingestion, inhalation	Slight hazard; an oxidizer; it can react with reducing materials
• Lithium Nitrate	Used in water/lithium bromide cooling systems as a corrosion inhibitor		Moderate toxicity w.r.t. ingestion and inhalation ingestion: dizziness, abdominal cramps, inhalation: weakness, headaches	Moderate hazard, by spontaneous chemical reaction
• Lithium Hydroxide	Used in water/lithium bromide cooling systems to control acidity		Moderate toxicity w.r.t. ingestion and inhalation; see sodium hydroxide, below	No flammability hazard
• 2-Ethylhexanol	Used in water/lithium bromide cooling systems as a wetting agent		Slight toxicity	Moderate hazard when exposed to heat or flame
• Sodium Chromate	Used in ammonia/water cooling systems as a corrosion inhibitor		High toxicity w.r.t. irritation, ingestion, inhalation	Low flammability
• Sodium Hydroxide	Used in ammonia/water cooling systems to control acidity		Moderate-high toxicity corrosive action on tissue causes burns; vapor can damage eyes; inhalation can damage upper respiratory tract	Low flammability hazard

public. The large areas of glass in solar collectors, for example, may pose breakage problems during installation, maintenance, or operation. However, this hazard, and the others summarized below, certainly do not exceed the hazards associated with using similar materials in other applications.

1. Collector Plumbing Problems: Leaks, Overpressurization, Boiling

Plumbing for solar systems must be stronger than conventional hot water plumbing because temperatures and pressures in excess of those of conventional domestic hot water systems occur in solar systems.

2. Use of Antifreeze and Anticorrosion Compounds in the Collector Loop

Solar systems must be designed with double walled heat exchangers between the collector loop and the domestic hot water supply. If this is not done, a significant consumer hazard will exist because a failure in the wall of a single-wall exchanger would contaminate the potable hot water supply with antifreeze or anticorrosion compounds.

3. Safety of Solar Absorption Cooling Devices

In general, there will actually be a slightly lower risk of explosion or leaks in solar absorption cooling units than in conventional absorption cooling units because the systems will operate at lower maximum temperatures.

4. Structural Issues: Roof and Wind Loading

The roofs of solar homes must withstand the additional weight of solar collectors. In general, this is not likely to present a problem, but it could limit the extent to which homes can be retrofitted with solar systems in a few parts of the country where building codes allow very light roof construction. Solar collectors must also be attached to the roofs with great care to prevent the possibility of accidents during high winds.

(5) Impact on Population Distribution

The development of solar energy will entail certain long-term trends with respect to population distributions. First, solar energy will encourage development of decentralized population patterns. This will result in further development of suburbs and of widespread, diffuse metropolitan areas rather than more concentrated cities. This is consistent with recent trends which show for the first time a net movement in population away from large cities and towards smaller cities.

Solar energy utilization may have an impact on the cost of living in the long term if life cycle solar energy costs are significantly lower than those of other energy forms. The widespread utilization of solar energy may encourage movement of population towards areas of the country with the highest degree of insolation, such as the southwestern states. (Solar desalinization technology is potentially important in such areas as well.) The accelerated economic development of these areas of the country will entail environmental impacts which would not otherwise have been expected.

* * * * *

The significant conclusions of this chapter are summarized below:

- Net energy supplied and net pollution should be key considerations in comparing solar energy utilization to total fossil fuel cycles (the coal cycle, for example, includes the extraction, processing and transportation of coal)
- Several studies indicate that solar heating and cooling systems may conserve on the order of 100 million tons of coal annually (optimistically by 1985, conservatively by 2000). This does not include additional savings which might be due to other solar technologies (e.g., solar electric generation and biomass conversion)
- Conservation of coal resulting from solar energy utilization will reduce acid water runoff and surface disfiguration associated with coal mining, and will conserve water resources. Reduced demand for electricity corresponds to a decrease in thermal pollution and effluent and solid waste residuals.

- Nationwide annual reductions in air pollution due to decreases in coal combustion may be on the order of 1.2 million tons of SO_x; 100,000 tons of TSP; and 700,000 tons of NO_x (optimistically by 1985, conservatively by 2000)

- The environmental benefits of solar heating and cooling systems outweigh the environmental penalties on a nationwide basis for net air and water pollution

- An important consideration in the design and manufacture of solar system components is that scarce or depletable materials or toxic substances not be used

- A recycling program should be an integral part of the marketing of solar systems

- Several other environmental aspects of solar energy utilization should be monitored as the technology is developed and commercialized, including aesthetic, consumer safety, meteorological and social considerations. Many of these other environmental considerations could be studied quantitatively in the same way that air pollution impacts were addressed in this report.

It is recommended that additional research be directed to the following:

- An economic comparison of the cost per quad of energy delivered by (1) solar heating and cooling systems and (2) conventional coal-fired power plants, for the period 1985-2000. Costs associated with generation of electricity include the costs of coal mining and surface restoration, coal transportation, construction and maintenance of power plants and transmission lines, and pollution control.

- Regional analyses of how utilization of solar heating and cooling may alleviate the need for construction of new fossil fuel power plants. These analyses should consider those regions where health effects of air pollution are or will be critical, or regions to which electricity will be supplied from power plants in remote areas where air quality is now pristine.

A more detailed evaluation of the potential of solar heating and cooling systems as a technological option for controlling air pollution by inclusion in Air Quality Maintenance Plans and State Implementation Plans.

II. THE ROLE OF SOLAR HEATING AND COOLING IN THE CONTEXT OF THE NATION'S OVERALL ENERGY PROGRAM

This chapter summarizes national programs for research and development of solar heating and cooling technology, and describes how these programs address environmental considerations. This discussion is presented in five sections:

- The national energy plan
- Federal agency responsibilities in the area of solar heating and cooling
- The role of Federal agencies in major solar heating and cooling demonstration projects
- The role of EPA in solar energy development
- Federal agencies concerned with environmental impacts of solar heating and cooling systems.

1. THE NATIONAL ENERGY PLAN

(1) The Goals of the National Energy Plan

The Energy Research and Development Administration (ERDA) has been designated the lead agency for energy-related research. As required by the Energy Reorganization Act of 1974 (PL 93-438), ERDA has identified national energy goals and has developed a national energy R&D program plan (ERDA-48)*, which identifies Federal energy programs and milestones necessary to obtain the objectives of the program.

The national energy plan focuses on accelerating commercial acceptance of technologies for the supply and conservation of energy. The specific goals of the plan include:

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* ERDA, A National Plan For Energy Research, Development, and Demonstration (ERDA-48), 2 volumes, June 1975.

- Expanding the domestic supply of economically recoverable raw materials used for producing energy
- Increasing the utilization of essentially inexhaustible domestic energy resources
- Transforming existing fuel resources into more desirable forms
- Increasing the efficiency and reliability of the processes used in the energy conversion and delivery systems
- Transforming consumption patterns to improve energy utilization of under used resources
- Increasing end-use energy efficiency
- Performing basic and supporting research and technical services related to energy
- Protecting and enhancing the general health, safety, welfare, and environment related to energy.

It should be noted from the last point above that a concern for environmental effects of energy utilization is a specific objective of the program.

The national energy plan was developed to be broad enough to include all the alternative technologies now being developed and yet flexible enough to permit development of a range of new energy technology options. This flexibility is important at the present time because of changes in resource availability, international politics, and domestic economic considerations. Recently, ERDA has emphasized energy conservation as the near-term objective of highest priority.

(2) Technology Options Addressed in the National Energy Plan

Achieving the goals of the national energy plan will require the development of new energy technologies. Several energy technology options have been identified in the program plan as the focus of an intensive RD&D effort. These technology options range from those which are currently commercially available to those not yet developed beyond the laboratory stage. The technologies are identified and prioritized below in Table 5:

Table 5
Ranking of RD&D Technologies

Priority	Energy Technology		
	Near-Term (<1985)	**Mid-Term (1985-2000)**	**Long-Term (>2000)**
Highest priority technologies*	Direct utilization of coal Converter reactors for nuclear Enhanced recovery of oil and gas Conversion of waste materials to energy	Gaseous and liquid fuels from coal Fuel from oil shale	Breeder reactors Nuclear fusion Solar electric
Other high priority technologies*		Geothermal Solar heating and and cooling	Fuels from biomass Hydrogen energy systems

Source: ERDA, *A National Plan for Energy Research, Development and Demonstration* (ERDA-48), 2 volumes, June 1975.

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* The priority scheme above reflects the capability of the technology to supply energy in the timetable indicated.

The development of these technologies could result in a contribution of up to 145 x 10^{15} Btu per year to the nation's energy supplies by the year 2000. This is equivalent to the energy supplied by 20 billion barrels of oil.

(3) The Role of Solar Heating and Cooling in the National Energy Plan

Solar technology, which until now has not made a significant contribution to the nation's energy supply, has the potential to make a significant impact as a new energy resource over the next several years.

As shown previously in Table 5, two solar energy options (solar electric, and solar heating and cooling) have been identified as technologies whose development can substantially augment our domestic energy supplies in the mid- and long-term.

- Solar Electric. The sun's radiant energy is converted to electricity, either by capturing radiant energy in collector systems and converting it directly into electrical power using photovoltaic devices, or by using the solar energy to heat a working fluid which is then used to operate a steam turbine power plant. The collector system for the latter approach, called solar thermal power generation, can be a solar "farm" (a large number of linear collectors used to heat the working fluid) or a solar furnace (light energy from different locations is focused on a single heat exchanger.) In a somewhat broader context, the use of wind or ocean thermal gradients as the input energy source can also be considered part of this technology.

- Solar Heating and Cooling. The sun's light energy is utilized to provide space heating or cooling, or domestic hot water, for buildings. While these buildings may be residential, commercial, industrial or agricultural, the residential and commercial type are considered to be the most promising applications.

  A typical solar heating system involves a flat plate collector using water or air as the working fluid, a sensible or latent heat storage system, and water or air as the space heating working fluid. Solar cooling may be accomplished using conventional heat actuated refrigeration systems or nocturnal radiation. The combined heating and cooling systems are ordinarily more economical than separate systems.

Together, solar electric and solar heating and cooling may contribute over six percent* of the additional energy anticipated from the development of all the alternative energy options listed in Table 5. In terms of equivalent barrels of oil, solar technology may save 1.6 billion barrels (about 9.1×10^{15} Btu's per year) by the year 2000. This total is composed of anticipated savings of the equivalent of nearly 600 million barrels of oil from the application of solar electric technology and the savings of the equivalent of over 1 billion barrels from solar heating and cooling systems alone.

Utilization of solar energy for heating and cooling is especially important because the technology is well developed and because the potential energy contribution is large. The energy consumed for space heating, air-conditioning, and water heating is currently about one fourth of all the energy consumed in the U.S.; essentially all of this energy is supplied by combustion of fossil fuels. This report is directed to the environmental aspects of solar technology which may supply a significant part of this percentage.

2. FEDERAL AGENCY RESPONSIBILITIES IN THE AREA OF SOLAR HEATING AND COOLING

To achieve the objectives of increased RD&D in the areas of solar heating and cooling identified in the national energy plan, an Interagency Task Force chaired by ERDA has prepared a comprehensive plan for management of the solar heating and cooling program and coordination of the activities of other Federal agencies participating in the program. This plan is discussed briefly in the following sections.

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* ERDA-48, volume 2 (6.3% of 144.5 quads by the year 2000)

(1) The National Plan for Developing Solar Heating and Cooling Technology

The objectives and schedule of the solar heating and cooling plan calls for commercial acceptance in time to make energy contributions before 1985, and for a substantial contribution to the nation's energy supplies by the end of the century. To accomplish this, ERDA has developed a National Plan for Solar Heating and Cooling (ERDA-23A, October 1975) to achieve the following objectives:

- Place emphasis on the early commercialization of heating and cooling systems in residential and commercial buildings
- Demonstrate this technology by 1979
- Involve private industry in the demonstration of this technology
- Direct Federal resources to disseminate technical, economic data, and other information to the public and private sectors
- Coordinate Federal activities directed at demonstrating this technology, improving system performance and reducing costs.

To achieve these objectives, the plan is structured into five program elements:

- A residential demonstration program
- A commercial demonstration program
- R&D in support of the demonstration programs
- A research and advanced systems development program
- An information dissemination program.

These program elements are discussed in more detail below.

The purpose of the residential and commercial demonstration programs in general is to enhance the marketability of solar heating and cooling systems. Specific goals to accomplish this objective are to demonstrate the feasibility of the technology, to encourage private sector participation (A&E firms, HVAC contractors, and the construction industry) and to build public and consumer confidence in solar systems. The programs are designed to lower system costs by stimulating demand among consumers and by providing a mechanism for the private sector to gain practical solar system expertise. Valuable by-products of the demonstration programs will be the collection of solar system operating data on a wide geographic basis.

Research in support of the demonstration programs will include the evaluation and testing of prototype systems and subsystems specifically for use in the demonstration program. Government support of industrial research in this area will result in a wider variety of technology options, and at an earlier date, than otherwise would be expected. Concurrently, research and development of advanced systems will be conducted to further develop the state-of-the-art of solar system components. The information dissemination program will collect and distribute information on the results of government RD&D programs and demonstrations to accelerate the widespread acceptance of this technology.

Estimates of funding levels of these five program elements, while still preliminary, indicate relative program priorities. Preliminary funding levels, which reflect the maximum number of demonstrations proposed in ERDA 23A, are shown in Table 6. This information indicates that the residential and commercial demonstrations may account for as much as 59 percent of the solar heating and cooling budget.

Table 6
Budget Levels for Solar Heating and Cooling Program FY 1975 - FY 1979

Program Element	Million Dollars	Percent of Budget
Residential Demonstration	69	22
Commercial Demonstration	112	37
Development in Support of Demonstrations	38	12
Advanced R&D	79	26
Information Dissemination	9	3
Total	307	100

Source: ERDA 23A

(2) Federal Agency Involvement in Solar Heating and Cooling RD&D

There were four laws passed in 1975 defining solar heating and cooling programs and Federal agency responsibilities:

- The Solar Heating and Cooling Demonstration Act of 1974, PL93-409, September 3, 1974
- The Energy Reorganization Act of 1974, PL93-438, October 11, 1974
- The Solar Energy Research, Development, and Demonstration Act of 1974, PL93-473, October 26, 1974
- The Federal Nonnuclear Energy Research and Development Act of 1974, PL93-577, December 31, 1974.

The legal requirements of these four acts and the specific requirements for interagency relationships have been addressed in detail by the Science Policy Research Division of the Library of Congress.* In the discussion which follows, general agency responsibilities are discussed.

The legislation mentioned above authorizes ERDA and other Federal agencies to carry out solar heating and cooling programs and to pursue the effective and early utilization of these systems. More precisely, ERDA's responsibilities in helping to develop solar energy technology, in addition to overall program management and coordination, include:

- The development of a solar energy data base
- Research and development of solar energy technologies
- Demonstration of solar heating and cooling energy technologies
- Establishment and operation of a solar energy information data bank
- Establishment of a Solar Energy Research Institute (SERI) to assist in advancing solar energy use and in furthering the dissemination of this technology
- International cooperation of the field of solar energy.

ERDA is directed to carry out these responsibilities in cooperation with the following departments and agencies:

- Department of Housing and Urban Development (HUD)
- Department of Defense (DOD)
- National Aeronautics and Space Administration (NASA)

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* Federal Interagency Coordination of Nonnuclear Energy Research and Development, June 6, 1975. Dorothy M. Bates, Science Policy Research Division, Congressional Research Service, Library of Congress.

- General Services Administration (GSA)
- National Bureau of Standards, Department of Commerce (NBS)
- National Science Foundation (NSF)
- Federal Energy Administration (FEA)
- Department of Agriculture (USDA)
- Department of the Interior (DOI)
- National Oceanic and Atmospheric Administration, Department of Commerce (NOAA)
- Department of Health, Education, and Welfare (HEW)
- Agency for International Development, Department of State (AID)
- Postal Service (USPS)
- Federal Trade Commission (FTC)
- Federal Power Commission (FPC).

Table 7 highlights the major areas of responsibility of these Federal agencies in the area of solar heating and cooling technology.

Having summarized the general responsibilities of each Federal department and agency participating in the program, it is appropriate to summarize agency responsibilities on a program element/task basis (Table 8).

3. THE ROLE OF FEDERAL AGENCIES IN MAJOR SOLAR HEATING AND COOLING DEMONSTRATION PROJECTS

The National Solar Heating and Cooling Plan (ERDA 23A) provides for the demonstration of solar technology for residential and commercial building applications to encourage commercial acceptance of these energy systems. The demonstrations will build public confidence in the technology and will enable the private sector to gain practical solar system expertise.

A limited number of buildings have already been equipped with solar heating or cooling systems, either initially or a retrofit basis. To date these have been largely R&D experiments designed to advance the state of the technology. Solar systems are operating in about 30 residences, two office buildings and four schools.

Table 7
Federal Agency Areas of Responsibility for Solar Heating and Cooling (Agency Basis)

Agency	Specific Areas of Responsibility
• FEA	. Mitigate the economic, institutional, and legal barriers hindering the commercialization of solar energy technologies . Stimulate market demand for these systems . Develop solar energy manufacturing capability . Assure that solar energy development activities are properly coordinated with other energy development activities and energy conservation programs
• HUD	. Jointly with ERDA, manage and operate the residential solar heating, cooling, and domestic hot water demonstrations . Jointly with NBS, develop performance criteria for residential solar heating and cooling systems . Disseminate information to promote the practical use of solar heating and cooling technology; establish a data bank[1] (to be managed by ERDA)
• NASA	. Provide component and system development, testing and evaluation support to the solar heating and cooling demonstration program . Conduct R&D on advanced solar heating and cooling systems . Providing program management expertise
• NSF	. Conduct basic and high risk research in the solar energy field

Table 7
(Continued)

Agency	Specific Areas of Responsibility
• NSF (Cont.)	. Educate personnel to perform solar energy RD&D
	. Disseminate information to the national and international community
• NBS	. Update performance criteria for solar heating and cooling components and systems. They will take the lead in coordinating the adoption of industry standards.
• NOAA	. Provide weather and insolation data
• DOD	. Arrange for installation of solar heating and cooling systems in buildings on Federal property
• USDA	. Manage commercial demonstrations related to agricultural applications of solar heating and cooling systems
• GSA, DOI USPS	. Conduct solar heating and cooling demonstrations in agency buildings
• HEW	. Identify buildings (hospitals, schools) for utilization in the commercial demonstrations
	. Determine the potential effects of substitution of solar energy systems on the low-income sectors of the population
• FPC, FTC	. Analyze regulatory, policy, and trade implications
• AID	. Assist in international aspects of the program

[1] The Solar Heating and Cooling Data Bank will collect, review, process, and disseminate this information and data as we provide retrieval and dissemination support for all government agencies, the academic community, nonprofit organizat and provide individuals upon request.

Table 8
Federal Agency Areas of Responsibility for Solar Heating and Cooling (Task Basis)

PROGRAM ELEMENT	LEAD AGENCY	PARTICIPATING AGENCIES[1]
1. RESEARCH AND DEVELOPMENT PROGRAM		
A. RESEARCH • Building Designs • Components & Materials • Advanced Systems • Systems Analysis • Insulation & Climatic Data	ERDA	HUD, NASA, FEA, DOD, NSF, GSA, NBS, NOAA
B. DEVELOPMENT FOR DEMONSTRATION PROGRAM • System Design & Development • Site Data Collection • Purchase/Development of Subsystem • Engineering Support • Test & Evaluation	ERDA	HUD, NASA, DOD, GSA, NBS
C. ADVANCED SYSTEMS DEVELOPMENT • System/Component Development • Integration of Subsystems	ERDA	NASA, DOD, NSF
2. RESIDENTIAL DEMONSTRATION PROGRAM		
A. PROGRAM DESIGN & MANAGEMENT • Program Preparation/Management • Environmental Impact Statements	ERDA/HUD JOINTLY[2]	NASA, FEA, DOD, GSA, NBS, NOAA, EPA
B. ESTABLISHMENT OF PERFORMANCE CRITERIA & STANDARDS • Develop and Monitor Standards • Certify Testing Labs	HUD[3]	ERDA, NASA, FEA, DOD, NSF, GSA, NBS
C. CONDUCT OF DEMONSTRATIONS • Subsystem, Site Selection • Construction and Ope[illegible]	HUD[4]	ERDA, NASA, FEA, DOD, NBS
D. DATA COLLECTION	HUD	ERDA, NASA, FEA, DOD, NBS
E. MARKET DEVELOPMENT TO ENHANCE COMMERCIAL & PUBLIC ACCEPTANCE	HUD	ERDA, FEA, DOD, NBS
3. COMMERCIAL DEMONSTRATION PROGRAM		
A. PROGRAM DESIGN & MANAGEMENT • Program Design • Technical Reqmt's • Environmental Impact Assessment	ERDA	HUD, NASA, FEA, DOD, GSA, NBS, USDA, USPS, DOI, HEW, EPA

[1] Support provided by utilizing resources of agency and/or providing consultation services.

[2] Joint overall responsibility for program and for program preparation/management. HUD is lead agency for balance of program elements.

[3] Joint responsibility with ERDA on developing intermediate minimum property standards.

[4] Joint responsibility with ERDA in selecting solar systems and in integration of them into demonstration project.

Source: ERDA 23A

Table 8
(Continued)

PROGRAM ELEMENT	LEAD AGENCY	PARTICIPATING AGENCIES
B. ESTABLISHMENT OF PERFORMANCE CRITERIA STANDARDS • Develop & Monitor Standards • Certify Testing Labs	ERDA	HUD, NASA, FEA, DOD, NSF, GSA, NBS, USDA, USPS, DOI, HEW
C. CONDUCT OF DEMONSTRATIONS • Subsystem, Site Selection • Maintain Demonstrations	ERDA	HUD, NASA, DOD, GSA, USDA, USPS, DOI, HEW
D. DATA COLLECTION	ERDA	HUD, NASA, FEA, DOD, GSA, NBS, USDA, USPS, DOI, HEW
E. MARKET DEVELOPMENT • Develop Financial & Consumer Acceptance Data on Solar Utilization • Define Analytical Technologies to Assess Economics of Solar Systems	ERDA	HUD, FEA, DOD, GSA, USDA, USPS, DOI, HEW
4. COLLECTION & DISSEMINATION OF INFORMATION • R&D Information • Demonstration Information • Supporting Development Information	ERDA/HUD[5]	All Federal Agencies Doing R&D
5. OTHER ACTIVITIES TO PROMOTE EARLY COMMERCIALIZATION		
A. ENERGY POLICY ANALYSIS	FEA, ERDA[6]	HUD, DOD, NSF
B. SOLAR PROGRAM DEFINITION & ANALYSIS	ERDA/HUD JOINTLY[7]	All Agencies Planning Construction
C. REGULATION & INCENTIVES • Utility Regulations • Configuration Standards • Building Codes • Environmental Alternatives	ERDA, HUD, FEA[8]	NASA, DOD, NSF, GSA, NBS, EPA, AID
D. INTERNATIONAL ACTIVITES	ERDA	HUD, NASA, FEA, DOD, NSF, GSA, NBS, AID

[5] ERDA has overall responsibility for this task and shares lead responsibility with HUD in disseminating information from the residential demonstration program. HUD is lead agency in relaying information to the building industry.

[6] FEA is lead agency in analyzing national energy policy as it relates to solar energy; ERDA is lead agency in removing constraints to commercialization and in defining the economics of alternative incentives to commercialization.

[7] The expanding of the existing program to equip Federal buildings with solar systems is a joint responsibility among ERDA, DoD and GSA.

[8] ERDA is responsible for truth in energy labeling; HUD for communication standards and building codes; FEA for utility regulations.

Source: ERDA 23A

A total of 2,000 residential and 400 commercial building demonstrations are planned by 1979.* The specific locations of these demonstration projects have not yet been defined. However, they probably will be located throughout all regions of the country. The proposed schedule for the demonstration program calls for construction to begin during 1976 and continue until 1979; from 1979 to 1985, the installations will be demonstrated and operated.

The responsibilities of Federal agencies in the solar heating and cooling program, and specifically in the demonstration programs, was included in Tables 7 and 8 given previously. In the following section, the role of each agency in the demonstration program is discussed in more detail.

- ERDA. In addition to being the primary agency managing the Solar Energy RD&D Program, ERDA also has the lead responsibility for implementing the commercial segment of the demonstration program, as well as coordinating the efforts of other agencies who also participate in this program. Though some statutory responsibilities do exist, a detailed management plan assigning various agency responsibilities for specific areas within this program has not yet been defined.

- HUD. The Department of Housing and Urban Development has joint responsibility with ERDA for managing the residential demonstration program. This portion of the program includes demonstrating solar space heating, domestic hot water solar systems, and combined solar heating and cooling systems to be used in residential buildings. HUD has the responsibility of selecting the specific designs of solar systems to be constructed and demonstrated. After defining the structural, geographic, and site requirements for these systems, HUD selects specific building designs and arranges for the installation of these solar systems.

  During the course of each demonstration, HUD will follow the operation of these systems, and through maintaining close liaison will ensure that pertinent technical information is disseminated to other participants of this program.

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* Assuming that the level 3 program defined in ERDA 23A is implemented.

NSF. Until ERDA was established, the National Science Foundation was the lead agency for solar energy research. NSF has funded several demonstration projects. These include demonstrations by academic institutions and private corporations, as well as a special school heating and cooling demonstration program. NSF's active participation in solar demonstrations will be limited to these projects.

Colorado State University has received NSF funding for solar home heating and cooling demonstrations. The university's 3,000 square foot floor area, two-story house with solar space heating, hot water heating and lithium-bromide absorption cooling has been in operation for about two years.

The Phoenix Corporation of Colorado Springs, Colorado, has received NSF funding to construct and test a solar-heated home. The solar-assisted heat pump concept is being demonstrated in this experiment and optimum operating specifications developed.

NSF also funded five solar demonstration projects located in public schools in:

- Warrenton, Virginia, built by Intertechnology Corporation
- Timonium, Maryland, built by AAI Corporation
- Minneapolis, Minnesota, built by Honeywell Corporation
- Boston, Massachusetts, built by General Electric
- Atlanta, Georgia, built by Westinghouse and Burt, Hill & Associates.

These demonstration systems have been in operation for at least a year and are developing operating data for system optimization.

NBS. The National Bureau of Standards has a demonstration house with solar heating and cooling located at their Gaithersburg headquarters. NBS is testing components and system operations and developing performance standards in cooperation with HUD and several private standard-setting organizations. Interim performance standards have already been developed which will be used by HUD in the nationwide residential demonstration program.

- DOD. The Department of Defense is planning several solar energy demonstration projects on their facilities around the country. Fifty residential solar heating and hot water heating demonstrations will be conducted during 1976 at Army, Navy and Air Force bases in different parts of the country, including Fort Polk, Louisiana; Fort Bragg, North Carolina; and Fort Belvoir, Virginia. A total of 35 new solar homes will be constructed and 15 houses will be retrofitted with solar systems.

  Other DOD demonstrations include:

  - A solar building at the Air Force Academy in Colorado Springs already in operation.

  - A planned complex of buildings to be heated and cooled by solar energy at Fort Carson.

  - Two Army-Air Force exchange buildings (50,000 square feet) at Kirtland Air Force Base in Albuquerque, New Mexico, and Randolph Air Force Base, Texas. These are projected for design during 1977-1978.

  - Several hot water heating demonstrations.

  - A battalion headquarters classroom building at Fort Hood, Texas, scheduled for completion by August 1976. ERDA funds are supplementing military construction funds for this project.

  - A $700,000 project for fiscal year 1976 to heat and cool 18 classrooms, an auditorium and a library at Fort Wachuka.

  - A conceptual design for a solar heated and cooled 80,000 ft.^{2} two-story range operations center at Yuma, Arizona, is being developed. ERDA funds will be sought for the solar system. If these funds do not become available, the building will be designed for possible solar retrofitting in the future.

  - The Army Reserves are conducting cost analyses of solar retrofitting of buildings at reserve training centers in Albuquerque, New Mexico; Seagoville, Texas; and Greenville, Mississippi.

- GSA. The General Services Administration is sponsoring two solar projects.

  - A seven-story office building in Manchester, New Hampshire

  - A one-story office in Saginaw, Michigan.

  Both are heating and cooling projects. The Manchester building will be operational by mid-1976; the Saginaw building by November 1976.

  GSA is also developing energy conservation guidelines for Federal government buildings and planning feasibility studies of retrofitting government offices with solar systems.

- USPS. ERDA is funding a solar heating and cooling demonstration at a 29,000 ft.^{2} post office in Boulder, Colorado. This is expected to be operational in 1978. The Postal Service is funding its own solar demonstration at its 6,000 ft.^{2} office building at Ridley Park, Pennsylvania. This system has been operational since September 1975.

4. THE ROLE OF EPA IN SOLAR ENERGY DEVELOPMENT

The charter responsibility of the Environmental Protection Agency is to develop and enforce standards necessary to protect human health and the environment. Thus, it is EPA's responsibility to ensure that the widespread utilization of solar energy systems will not result in major hazards to human health or in serious environmental pollution. It is economically advantageous to eliminate potential environmental problems during the definition and development of a technology rather than to take remedial action after the technology is in widespread use. Thus, a comprehensive evaluation of all potential environmental aspects of solar energy technologies will result in a greater spectrum of technological options for urban or regional environmental planning.

Consequently, EPA will satisfy its charter responsibility by encouraging the development of solar technologies which are environmentally acceptable with respect to EPA standards and guidelines. This objective will be achieved through consultation with participating agencies during all phases of technology development. This interagency cooperation will guarantee that environmental considerations are addressed at the earliest point in the development process. This will minimize the necessity of promulgating regulations to correct environmental problems subsequent to widespread utilization of solar systems. Table 9 presents several environmental goals toward which the development of solar technology should be directed. For these goals to be achieved, EPA should be involved in consultations with the agency or organization sponsoring research or development.

5. FEDERAL AGENCIES CONCERNED WITH ENVIRONMENTAL IMPACTS OF SOLAR HEATING AND COOLING SYSTEMS

A number of Federal agencies are responsible for identifying and mitigating the environmental impacts resulting from solar heating and cooling systems. As stated previously, EPA's general responsibility is to develop and enforce standards, as required, to protect human health and the environment.* During the heating and cooling demonstration programs, EPA will assist ERDA as follows:

- To provide consultation services to ERDA in preparation of environmental assessments and environmental impact statements for the residential demonstration program
- To assist ERDA in evaluating environmental assessments prepared by contractors for the commercial demonstration program, and to assist in preparation of environmental impact statements
- To monitor the plans and construction of ERDA's demonstration program and perform environmental studies of alternatives to the demonstration program aimed at reducing any undesirable impacts.

During the solar heating and cooling demonstration program, the Council on Environmental Quality (CEQ) is responsible

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* There are currently no Federal or local environmental standards concerning pollution resulting from utilization of solar heating and cooling systems.

Table 9
Appropriate Agency Consultation With EPA* During Solar Energy Research and Development

Solar Energy Related Environmental Goals	Consulting Agencies
● Equipment should contain minimum amounts of materials whose production has significant environmental impacts	ERDA, FEA, HUD, NBS, NSF
● Equipment designs should avoid using scarce or depletable materials, or materials for which the production is energy-intensive	ERDA, FEA, HUD, NBS, NASA
● Recyclable materials should be used when possible in equipment construction	ERDA, FEA, HUD, NBS
● Toxic working fluids and materials should not be used in case of accidental release or prolonged exposure	ERDA, HUD, NASA, NBS
● Institutional and legal barriers, such as "sun rights", should be considered during system design and implementation	ERDA, FEA, HUD
● Implications of large collector arrays, such as potential climate modification, should be considered	ERDA, NOAA
● Minimize the potential release of air pollutants such as fluorocarbons from working fluids	ERDA, NOAA
● Coordinate long term regulatory, regional and urban planning policy related to overall energy and environmental implications of solar energy utilization	ERDA, CEQ, FEA, FDC

*Responsibility for EPA energy related environmental and health research and development, as well as control technology R&D, resides with the Office of Energy, Minerals and Industry of EPA's Office of Research and Development. Cognizance for R&D activities related to pollution control technology for solar and advanced systems is delegated to OEMI's Industrial Environmental Research Labs in Cincinnati, Ohio.

for conducting continual evaluations of the adequacy of environmental assessments developed during the program. In the preparation of environmental impact statements for the commercial demonstrations:

- ERDA has lead responsibility
- DOD and EPA provide consultation services.

For the environmental impact statements required for the residential demonstrations:

- HUD had lead responsibility
- ERDA provides technical support
- FEA and EPA provide consultation services.

Based on the results of these environmental impact statements, alternatives to reduce negative environmental impacts may be developed by the following agencies:

- ERDA and HUD have joint responsibility
- NASA, FEA, NSF, and NBS to technical support, and
- EPA, DOD, and GSA to provide consultation services.

Since ERDA is managing and coordinating the activities related to the National Solar Heating and Cooling Program, ERDA will maintain current information on technical and policy developments concerning the environmental aspects of solar technologies. The objectives of this activity at ERDA will be to:

- Identify and project the environmental effects[*] of solar technology.

- Minimize any adverse effects.

- Maintain an information base to formulate and help substantiate policies aimed at assuring that solar heating and cooling systems are developed in an environmentally acceptable manner.

ERDA will keep abreast of developments within other Federal agencies in the area of solar heating and cooling and will seek to identify and report on any predicted environmental consequences. Early and continuous involvement of ERDA with EPA and CEQ is necessary to ensure that the environmental impacts identified in Chapter I, and others which emerge over time, are considered as solar energy technologies are developed and commercialized.

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[*] Environmental effects of solar energy utilization have not yet been studied in detail and there does not exist any national program yet to do this.

* * * * *

It is advantageous to address environmental considerations as early as possible in the development of a technology. It has been emphasized in the previous discussion that appropriate federal coordination is necessary for the environmentally acceptable development of solar heating and cooling technologies. The following chapter presents a methodology for evaluating the impacts of solar system application on air quality in a specific geographical area. This example is intended to illustrate the kind of continuing analysis that should be conducted to investigate environmental costs and benefits of solar technology as it develops.

III. ASSESSMENT OF AIR QUALITY IMPACTS OF SOLAR HEATING AND COOLING SYSTEMS

As discussed in Chapter I, solar heating and cooling systems will have a direct effect on two sources of air pollution emissions:

- A decrease in fuel combustion for space conditioning and hot water
- An increase in the production of materials from which solar system components are fabricated.

This chapter addresses the decrease in emissions in urban areas due to savings of local combustion of fossil fuels and electricity produced at central power plants. The potential increase in emissions, related to increased production of materials, in most cases will not occur in those urban areas where the solar systems are used. Consequently, the assessment of air quality impacts in urban areas, presented in this chapter, does not include those industrial emissions.

The assessment of air quality impacts is presented in five sections:

- The fuel savings from solar heating and cooling systems. This section describes all the factors which influence the potential fuel savings resulting from the use of solar systems. Mathematical relationships are developed which define the average energy load for various building types, the potential, per-building fuel savings due to solar systems, the number of buildings which may be equipped with solar systems, and total areawide fuel savings. The equations presented in this section form a mathematical model for projecting the fuel savings due to solar heating and cooling systems for any urban area, as a function of the rate of acceptance of solar systems in that area. A glossary of terms is provided at the end of this chapter to serve as a guide for understanding the relationships developed in the chapter. Additional input data required for the model are also given in this section. These data were taken from several sources; primarily the Phase "O" solar heating and cooling study funded by the National Science Foundation (NSF).*

- Changes in pollutant concentrations due to reduced fuel combustion. This section discusses the changes in emissions and ambient air quality which may result from solar-induced fuel savings.

- Summary of the methodology. The terminology and key equations defined in the two previous sections are summarized in this section.

- Sample application of the methodology. In this section, actual data for the Baltimore, Maryland SMSA, and postulated values for key input parameters are combined to demonstrate how the methodology can be used to forecast changes in annual emissions.

- Parametric analysis of regional emission savings. A key feature of the methodology is that it can be used for parametric analyses. In this section that feature is demonstrated by simplifying the equations to express emission changes as a direct function of only one parameter (rate of market penetration). From the simplified equations emission forecasts corresponding to several assumed market penetration rates are then developed for a hypothetical urban area.

1. THE FUEL SAVINGS FROM SOLAR HEATING AND COOLING SYSTEMS

The development of mathematical relationships for estimating the potential fuel savings due to solar energy utilization is presented in six sections:

- Definition of climatic regions and building categories

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* General Electric, Solar Heating and Cooling of Buildings, Phase "O", Feasibility and Planning Study Final Report, May 1974, (hereafter cited as GE Phase "O" Report). This major study was directed toward assessing the feasibility of solar heating and cooling systems and planning for proof-of-concept experiments.

- Energy load for each building type
- Potential energy savings per building
- Potential fuel savings per building
- Number of buildings equipped with solar systems
- Areawide fuel savings.

(1) Definition of Climatic Regions and Building Categories

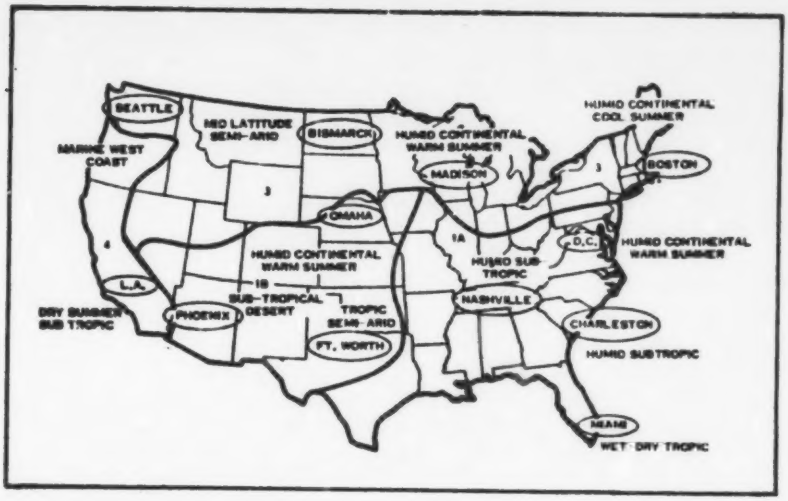
The fuel or energy displaced by solar systems will be either fossil fuels burned on site, or electricity generated at a central station, or both. The potential fuel savings are based on:

- The energy requirements for residential and commercial buildings
- The portion of the energy load supplied by the solar system, and the fuel displaced
- The number of buildings equipped with solar systems.

Each of the above considerations are regional in nature, varying with climate, insolation levels, and the many factors influencing the commercial acceptance of solar systems. In addition, energy load and fuel savings will vary with building type, because different building types correspond to different heating/cooling demands, construction, and usage.

In order to facilitate the analysis of energy savings and air pollution impacts, generalizations concerning building variations and regional climatic factors may be made. If it is assumed that climatic conditions are approximately uniform over certain regions of the country, then the Continental United States may be divided into general climatic regions. If it is also assumed that on the basis of energy characteristics, residential and commercial buildings may be classified into representative building categories, then the heating and cooling loads for typical buildings, representative of all buildings of that category, may be defined. It should be clear that there may be significant climatic variation within regions, and that a significant amount of detail is lost by generalizing about building types and regional climatic conditions; the generalizations are used to simplify the analysis.

A climatological regionalization scheme is shown in Figure 7, where each of the 12 climatic regions is designated by a city where the climate is representative of the region. Climatic data for each city are given in Table 10. Characteristics for 17 general building types are given in Table 11. These characteristics may be used to define energy demands for the buildings of each category. The criteria used to define building types were that the categories reflect buildings in place or to be constructed in large volume, and the building characteristics and uses be representative.



Source: GE Phase "0" Report (May 1974).

FIGURE 7
Regional Climatic Classification

(2) Energy Load for Each Building Type

There are three components of the energy load of a building which are under consideration here: space heating, space cooling, and domestic hot water. For

Table 10
Climatic Data for Sample Cities

Location	Winter Design Temp. ~°C[1]	Summer Dry Bulb Temp. ~°C[2]	Insolation (Langley/hour)	Design Relative Humidity (%)
Madison	-20.5	31.1	50.0	52
Charleston	- 1.1	33.8	52.0	64
L.A.	6.6	32.2	58.1	49
Boston	-12.2	31.1	46.2	55
D.C.	- 7.2	33.3	53.6	53
Phoenix	1.1	41.1	65.8	31
Miami	8.8	31.6	53.0	65
Omaha	-18.3	34.4	53.9	50
Bismarck	-28.3	32.7	55.6	48
Nashville	- 8.8	35.0	51.9	53
Seattle	0.0	26.1	52.0	62
Ft. Worth	- 4.4	37.7	62.3	48

[1] ASHRAE 97-½% values.

[2] ASHRAE 2-½% values.

Source: GE Phase "O" Report.

Table 11
Characteristics of Typical Buildings

No.	Building Type Description	Number of Stories	Floor Area		Wall Area Sq. Ft.	Window Area		Height/ Story, Ft.	Volume, Cu. Ft.		Infiltration/ Ventilation Requirements CFM/sq. ft. floor
			Per Story	Total Sq. Ft.		% of Wall	Total Sq. Ft.		Above Ground	Below Ground	
1	Residential, Single Family	2 + B	900	1,800+B	2,196	15	330	9	16,200	B	0.25
2	Residential, Multiple High Rise	14	10,350	145,000	51,156	20	10,231	9	1,306,000	0	0.25
3	Residential, Multiple Low Rise	3	200	21,600	12,700	20	2,560	9	79,400	0	0.25
4	Hotel/Motel, High Rise	14	10,350	145,000	51,156	20	10,231	9	1,305,000	0	0.25
5	Hotel/Motel, Low Rise	2	20,000	40,000	10,800	30	3,240	9	360,000	0	0.25
6	Office Building, High Rise	30	20,000	600,000	216,000	30	64,800	12	7,200,000	0	0.25
7	Office Building, Low Rise	2	10,000	20,000	8,800	20	1,760	11	220,000	0	0.25
8	Warehouse	1	60,000	60,000	25,000	0	0	25	1,500,000	0	0.50
9	Industrial, Light Process Load	1	100,000	100,000	28,000	5	1,400	20	2,000,000	0	1.50
10	Industrial, Heavy Process Load	1	200,000	200,000	43,200	0	0	24	4,800,000	0	2.00
11	Educational, K to 12	1	52,000	52,000	12,880	25	3,200	14	728,000	0	0.75
12	College/University	2	25,000	50,000	16,900	25	4,225	13	650,000	0	0.75
13	Auditoriums	1 + B	22,000	30,000	15,500	0	0	25	550,000	80,000	0.75
14	Health Care, Clinic	2	4,500	9,000	7,280	10	728	13	117,000	0	0.75
15	Hospital	4	12,000	48,000	23,200	20	4,640	13	624,000	0	1.00
16	Retail, Merchandise Mall	1	750,000	750,000	99,000	5	4,950	18	13,500,000	0	0.50
17	Retail, Individual Store	1	5,200	5,200	5,440	20	1,088	16	83,200	0	0.50

1 ft. = 0.305 m

Source: GE Phase "O" Report (adapted from data supplied by the Ballinger Co.)

a given building type, the thermal load for each of these three components, regardless of fuel supply, is a function of:

- Building shape and dimensions
- Construction (materials)
- Insulation
- Fenestration
- Use patterns
- Internal loads[*]
- Climate (degree-days, peak heating/cooling loads, wind, humidity)
- Ventilation requirements.

Estimates of the energy demand B_{jm} (in Btu) for each building type j and application m (heating, cooling, hot water) in each region are given in Tables 12 and 13.[†]

The data in Table 12 are based on an hour-by-hour simulation of heating and cooling loads which included the following parameters:

- Size, shape, construction, and orientation of each "typical" building
- Ambient wind, insolation, and temperature
- Transient electrical loads
- Infiltration loads

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[*] Heat generated within the building by lights, appliances, and occupants.

[†] Source: The data presented in Tables 12 and 13 are the most current estimates of energy loads (by type of building) for representative cities in each climatic region of the country. These data, based on energy loads originally presented in the GE Phase " Report, were updated with the assistance of GE, to provide the bes possible data base for this assessment.

Table 12
Heating and Cooling Loads, B_{jm}
(10^6 Btu/Year)

Location	Cooling Load By Building Type																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Madison	20	3,280	1,417	8,595	328	16,008	730	–	–	–	1,758	2,017	[illegible]	233	3,378	[illegible]	183
Charleston	88	19,536	7,379	51,987	3,755	87,835	2,080	–	–	–	6,786	[illegible]	2,841	1,101	10,894	163,279	771
L.A.	8	2,063	1,254	5,669	180	27,592	1,114	–	–	–	1,486	2,507	40	243	4,941	86,307	236
Boston	20	3,244	1,184	8,437	380	20,077	720	–	–	–	1,383	1,890	384	232	4,594	47,866	193
D.C.	33	5,412	1,870	14,286	719	25,179	792	–	–	–	1,900	2,624	789	336	4,102	98,000	267
Phoenix	158	19,862	8,072	52,032	6,231	72,162	2,678	–	–	–	5,312	6,979	2,334	927	10,290	151,839	739
Miami	233	45,633	16,958	120,564	11,224	135,275	4,277	–	–	–	14,244	16,064	6,570	2,306	21,078	223,962	1,622
Omaha	35	8,881	3,368	23,576	1,598	36,270	1,186	–	–	–	3,193	3,891	1,349	510	5,807	84,879	398
Bismarck	15	2,314	871	6,271	519	14,293	542	–	–	–	1,880	1,409	283	182	2,407	33,865	137
Nashville	101	18,927	2,730	50,080	1,198	62,063	1,329	–	–	–	2,973	8,882	3,143	1,008	9,883	146,184	716
Seattle	9	1,530	929	3,948	750	12,241	451	–	–	–	1,229	1,178	121	127	2,168	29,864	112
Ft. Worth	150	22,368	9,002	58,891	5,562	73,603	2,456	–	–	–	6,876	8,117	3,616	1,147	11,063	167,083	819

Source: Update of data presented in Solar Heating and Cooling Buildings Phase "O" Report by GE to NSF, May 1974

Notes

1. Design conditions: Winter indoor design temperature: 70° F (21° C) daytime; 65° F (18.3° C) nighttime
   Summer indoor design temperature: 78° F (25.5° C) dry bulb at 50 percent relative humidity
   Climatic conditions: NOAA observed climatological data for one year man-hourly basis.

2. Model used for hourly load simulation: GE Building Transient Thermal Load program.

3. Note that the degree-days for the "typical" year for which NOAA data were used deviated from 30-year-averages by as much as 28 percent.

4. The calculations are consistent with the methods and data given in the ASHRAE *Handbook of Fundamentals.*

*Building types defined in Table 13.

Table 12
(Continued)

Location	Heating Load By Building Type																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Madison	161	8,102	11,022	73,764	4,873	2,824	1,479	9,867	41,865	105,730	11,608	9,253	6,650	2,071	9,460	88,805	1,127
Charleston	70	3,571	3,189	32,583	447	264	353	5,470	17,876	43,140	6,722	2,186	2,088	731	1,097	16,764	188
L.A.	46	1,728	1,700	16,828	422	240	219	3,883	10,446	32,783	3,161	1,382	972	377	380	9,085	180
Boston	139	6,596	9,088	80,098	3,833	2,081	1,137	8,128	34,010	88,848	9,320	7,308	4,484	1,860	6,786	80,840	878
D.C.	112	6,053	7,840	86,407	3,080	1,766	931	8,280	30,300	86,137	8,280	6,762	4,180	1,440	3,877	80,800	788
Phoenix	42	1,498	1,612	13,889	1,028	884	128	3,316	10,823	26,837	2,863	2,133	789	410	884	21,289	133
Miami	5	143	848	1,173	121	83	5	270	718	1,828	60	83	188	188	88	717	2
Omaha	148	6,480	9,029	88,040	3,786	2,130	1,186	8,236	34,641	88,300	9,364	7,882	4,443	1,873	7,848	71,823	913
Bismarck	183	8,721	11,140	88,882	5,875	3,384	1,776	18,112	80,817	131,448	13,830	11,376	6,828	2,482	11,807	108,878	1,282
Nashville	85	5,508	4,280	60,128	2,378	1,351	713	6,281	28,111	67,180	7,518	4,888	3,825	1,274	3,188	38,482	891
Seattle	108	7,032	6,381	63,783	3,561	2,022	1,076	11,028	30,248	[illegible]	9,764	6,700	4,833	1,084	6,251	57,411	761
Ft. Worth	76	3,104	3,762	28,257	846	478	411	3,876	16,889	40,221	4,168	2,720	2,128	708	1,738	23,281	370

*Building types defined in Table 13.

Table 13
Hot Water Loads, B_{jm}

j	Building Type (j) Description	Average Annual Energy Demand (10^6 Btu)	Average Daily Water Demand (Gallons)	Typical Hot Water Temperature, °F (°C in Parenthesis)
1	Residential, Single Family	13.3	45	150 (65.5)
2	Residential, Multiple High Rise	1,253	4,100	150 (65.5)
3	Residential, Multiple Low Rise	265	900	150 (65.5)
4	Hotel/Motel, High Rise	465	2,000	130 (54.0)
5	Hotel/Motel, Low Rise	218	1,000	130 (54.0)
6	Office Building, High Rise	569	3,000	120 (49.0)
7	Office Building, Low Rise	19	100	120 (49.0)
8	Warehouse	4	20	115 (46.0)
9	Industrial, Light Process Load	133	730	115 (46.0)
10	Industrial, Heavy Process Load	266	1,040	115 (46.0)
11	Educational, K to 12	95	500	115 (46.0)
12	College/University	142	750	120 (49.0)
13	Auditoriums	47	250	120 (49.0)
14	Health Care, Clinic	57	200	145 (63.0)
15	Hospital	1,490	5,250	145 (63.0)
16	Retail, Merchandise Mall	19	100	115 (46.0)
17	Retail, Individual Store	2	10	115 (46.0)

Source: GE Phase "O" Report.

Note: (1) Based on average water temperature of 50° F (10° C).

(2) Process hot water not included.

- Personnel loads
- Thermostat settings.

Detailed computer* analyses were performed by General Electric for six buildings in nine locations (54 total combinations). The values for the other 150 combinations in the table are based on less detailed load calculations, adjusted to reflect the results of the detailed simulations.

The hot water loads in Table 13 are representative for the average building types defined previously. It is assumed that the loads are independent of geography. Note that the energy requirement depends on the input and delivered temperature, as well as the quality, of hot water.

(3) Potential Energy Savings Per Building

The maximum amount of energy per square meter which in theory could be used for heating and cooling is limited by latitude and several atmospheric conditions, primarily cloud cover and atmospheric clarity. For a given density of collectable solar energy, there are several factors which determine the thermal capacity of a solar system. The single most expensive component of a solar system which limits the system's thermal capacity is the collector. Consequently, because of cost considerations, physical limits on the space available for solar collectors, and the necessity for designing heating/cooling system capacities for peak requirements, solar systems are ordinarily designed to provide less than 100 percent of a building's energy load.

The life-cycle economic optimization of a solar heating and cooling system involves trading-off several design parameters including:

- The type of application (space heating, space cooling, hot water, or a combination) for which the solar system was designed to supply energy.

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* Building Transient Thermal Load (BTTL) computer program prepared by General Electric and reported in Solar Heating and Cooling of Buildings, Phase "O" Report, May 1974.

- Type of system components used: trade offs usually involve working fluids, thermal storage systems, and heat exchangers or pumps.
- Performance criteria and materials for selected components. Parameters which have the highest cost impact are collector area and collection efficiency and thermal storage capacity.
- System reliability and maintenance requirements.

Life-cycle cost optimization also involves the cost of competing fuels and the period over which costs are to be amortized (which may be less than the solar equipment lifetime).

Minimization of solar equipment costs and maximizing economic benefit usually results in systems which are designed to provide approximately 30 percent to 70 percent of heating and cooling requirements. This means that conventional heating and cooling equipment must be installed in addition to the solar system, although perhaps at reduced capacity.

The portion of building energy load supplied by solar systems of optimized design, therefore, will vary with region and with building type. If the percentage of the load for each building type j and application m which is supplied by solar energy is F_{jm}, (where $0 \le F_{jm} \le 1.0$), then the potential energy savings per building (in Btu) is given by:

$$E_{jm} = B_{jm} \times F_{jm} \qquad (1)$$

Note that the total energy per building supplied by solar energy is given by: $\sum_{m} E_{jm}$.

Typical values for F_{jm} by building type and location are given in Tables 14 and 15 for space heating and cooling. These data reflect hour-by-hour simulations of solar performance, and assume a heat

Table 14
Energy Savings, Space Heating, and Hot Water (F_{jm})
(Fraction of Total Load)

Space Heating

Location	Building Types																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Madison	.32	.08	.31	.08	.37	.07	.36	.41	.23	.19	.38	.25	.25	.22	.14	.53	.41
Charleston	.72	.15	.65	.15	.95	.10	.75	.53	.38	.34	.48	.62	.46	.42	.62	.85	.80
L.A.	.99	.47	1.00	.47	.43	.21	1.00	.81	.72	.60	.92	.93	.89	.85	1.00	1.00	1.00
Boston	.39	.12	.42	.12	.49	.07	.47	.48	.28	.23	.47	.34	.31	.28	.18	.62	.80
D.C.	.46	.12	.47	.12	.54	.08	.53	.49	.33	.25	.49	.41	.35	.32	.32	.72	.54
Phoenix	1.00	.39	.98	.39	.92	.13	1.00	.82	.62	.58	.86	.72	.87	.69	.86	1.00	1.00
Miami	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Omaha	.33	.11	.37	.11	.43	.07	.40	.45	.26	.21	.56	.21	.28	.24	.16	.59	.45
Bismarck	.46	.11	.31	.11	.53	.11	.30	.41	.18	.18	.31	.34	.34	.30	.18	.77	.33
Nashville	.42	.07	.34	.07	.43	.03	.34	.31	.19	.15	.28	.21	.20	.19	.13	.32	.31
Seattle	.36	.07	.26	.07	.33	.05	.20	.26	.17	.18	.18	.24	.28	.26	.16	.65	.15
Ft. Worth	.69	.15	.58	.15	.85	.07	.67	.61	.38	.31	.59	.50	.40	.40	.41	.79	.67

Source: GE Phase "O" Report.

Hot Water

A representative estimate for the fraction of total hot water load supplied by solar systems is 0.9 for all building types. Specific values depend on a number of system design parameters and patterns of demand.

Table 15
Energy Savings, Space Cooling, (F_{jm})
(Fraction of Total Load)

Location	Building Types													
	1	2	3	4	5	6	7	8-11*	12	13	14	15	16	17
Madison	.96	.27	.61	.27	.96	.06	.52	–	.31	.65	.40	.07	.50	.54
Charleston	.77	.06	.34	.06	.45	.03	.34	–	.11	.30	.14	.04	.35	.30
L.A.	.89	.70	.77	.70	.88	.03	.56	–	.37	.88	.70	.08	.57	.64
Boston	.98	.18	.65	.18	.80	.05	.60	–	.31	.60	.38	.08	.55	.80
D.C.	.72	.15	.55	.15	.70	.03	.43	–	.19	.46	.25	.07	.38	.42
Phoenix	.83	.14	.59	.14	.63	.03	.53	–	.26	.63	.32	.08	.55	.58
Miami	.83	.04	.24	.04	.30	.02	.26	–	.08	.20	.10	.03	.30	.22
Omaha	.90	.10	.53	.10	.52	.03	.45	–	.17	.44	.22	.04	.60	.43
Bismarck	.97	.57	.77	.57	.97	.10	.78	–	.60	.97	.69	.21	.80	.88
Nashville	.96	.07	.70	.07	.55	.03	.43	–	.15	.33	.30	.05	.37	.39
Seattle	.85	.53	.75	.53	.75	.10	.65	–	.50	.75	.60	.17	.65	.70
Ft. Worth	.90	.07	.67	.07	.52	.03	.41	–	.15	.32	.30	.05	.38	.39

*Building types 8-11 are not normally cooled.

Source: GE Phase "O" Report.

exchange system for heating, an absorption air conditioner for cooling, and a collector area equal to 50 percent of the roof area (the maximum for a peaked roof).

(4) Potential Fuel Savings Per Building

In order to identify the quantity of each fuel saved, the fuels which would have been burned in each individual building in the absence of the solar system must be identified, and the portion of the heating, cooling and hot water demand supplied by solar energy in each individual building must be determined. Define the fuel use factor $FFN_{jkm}(T)$ for all new buildings of type j as the fraction of the load for each application m which is supplied by fuel k* in year T. Then:

$$\sum_{k} FFN_{jkm} = 1.0 \text{ (when j and m are constant)} \qquad (2)$$

For each building type j and year T the fuel use factors FFN_{jkm} form a matrix as follows:

FUEL (k)*

Application (m)	Elec.	Dist. Oil	Resid. Oil	Nat. Gas	Coal	Other
Heating						
Cooling						
Hot Water						

All factors are less than unity, and the sum of all rows equals one.

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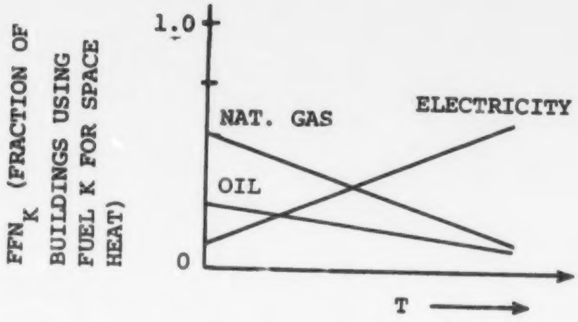
* On site (end use) consumption.

Since the fuel use factors are time-dependent, the factors for a given building type for space heating when plotted graphically, might appear as follows:



Fuel savings depends upon the efficiency of the furnace, air conditioning system and hot water heater. Define HE_{km} as the efficiency for fuel k and application m; typical values for HE_{km} are given in Table 16.

Table 16

Typical Heating/Cooling Equipment Performance (HE_{km})

Heating Equipment Efficiency*

Application (m)	Fuel (k)		
	Electricity†	Natural Gas	Heating Oil
Space Heating	1.00	0.65	0.60
Hot Water	0.60	0.60	–

*Defined as (Btu supplied)/(Btu of fuel input).

†Excluding power plant generating efficiency (i.e., (Btu supplied)/(Btu of electricity used).

Cooling Equipment Coefficient of Performance**

Application (m)	Fuel (k)		
	Electricity	Natural Gas	Heating Oil
Space Cooling	2.50	0.60	–

**Defined as (Btu removed)/(Btu of fuel input).

The annual per-building savings of fuel k is then given by:

$$U_{jk} = \frac{1}{C_k} \sum_{m} \left(FFN_{jkm} \times E_{jm}/HE_{km}\right) \qquad (3)$$

where C_k is the Btu content of the fuel (Btu per unit fuel); E_{jm} was defined by equation (1).

(5) Number of Buildings Equipped With Solar Systems

The number of buildings in which solar heating and cooling systems will be installed depends on how many buildings of each type are heated and cooled by conventional means and on the rate of market acceptance of solar systems. The percentage of buildings which are heated and cooled depends on climatic conditions.

The extent and rate at which solar systems penetrate the heating and cooling market will vary geographically and depends on several factors. The most important factor is probably cost. Though operating costs are lower than for conventional systems, solar systems have a higher initial cost. Thus, most solar applications are economically attractive only when life-cycle costs are considered. The most important cost factor for conventional systems in a life-cycle cost comparison is the cost (and availability) of conventional fuels. The economic attractiveness of solar systems, therefore, depends primarily on the initial cost of the solar system, the cost of competing fuels, and the willingness of the consumer to base decisions on life-cycle, rather than initial, costs.

There are additional cost considerations which affect market acceptance. Because solar technology has not gained widespread acceptance, the maintenance, repair, and operating costs are not well established historically and are considered by many consumers to be high. The life-cycle cost argument is based on future fuel prices, which can be estimated but not guaranteed. The risks associated with solar systems influence economic considerations, specifically insurance, financing, and resale value.

Several other barriers to market acceptance will affect market penetration. There are currently no standards of performance, quality, or safety for solar systems. Thus, poor quality equipment might be introduced in the market and damage consumer confidence. Although several companies with significant investment capital resources are entering the solar equipment market actively, it is expected that mass production of solar components will not begin until the market matures considerably. Hence, costs will remain high due to piecework production.

There are social barriers to acceptance, such as public confidence in the technology and in the solar industry. There is a general lack of awareness of solar system capabilities and limitations among manufacturers and the public, many of whom question the performance of solar systems. Existing solar demonstration houses are considered by many to be aesthetically unappealing, a fact which adds to the unwillingness of a larger portion of the public to invest in solar systems.

One important factor influencing the rate of acceptance of solar systems will be the enactment of various types of incentives to encourage the utilization of solar technologies. Incentive programs proposed to stimulate the solar energy market may be categorized into five general groups:

- Tax incentives: income, sales, property, or usage taxes
- Finance incentives: loans and bonds
- Utility rate restructuring
- Grants or subsidies for consumers and manufacturers
- Information and demonstration programs.

Of the state or local incentives proposed or already enacted, property tax incentives have received the greatest attention. Eight states have passed property tax exemptions and at least 21 are considering property tax proposals. How actively Federal, state, and local governments establish incentive programs will have a direct impact on the rate of utilization of solar technology.

The remainder of this subsection is devoted to development of a method to forecast the number of buildings equipped with solar systems. This method is based on parameterization of the rate of market penetration of solar systems.

The stock of buildings at any time is determined by the demolition rate and the rate of new construction. These rates may be expressed as the percentage of existing buildings which were demolished or built per unit time. In other words, if in a given period of time ΔT (e.g., a year), ΔN buildings were demolished, and the total number of buildings at some point during the period was N, then the demolition rate is equivalent to $\frac{1}{N} \cdot \frac{\Delta N}{\Delta T}$ (percent per unit time). A similar approach may be used to define the rate of new construction. Using $d_j(t)$ as the demolition rate for building type j, $c_j(t)$ as the rate of new construction, and $N_j(t_o)$ as the number (stock) of buildings at time t_o, the total number of buildings at time t ($t > t_o$) is given by:

$$N_j(t) = N_j(t_0) \exp \left\{ \int_{t_o}^{t} [c_j(t) - d_j(t)] \, dt \right\} \qquad (4)$$

where $[c_j(t) - d_j(t)]$ is the net rate of building stock change $P_j(t)$.

Discrete values for the functions $c_j(t)$ and $d_j(t)$ may be determined from historical data if the number of new starts or demolitions in a given time period are known, and the stock of buildings (at the beginning, midpoint or end of each time period) or an average stock over the time period is known. A curve may be fitted to the discrete points to produce continuous functions for $c_j(t)$ and $d_j(t)$.

Solar systems may be either installed in new buildings or retrofitted into existing buildings. If the rate at which solar systems are installed in new buildings is $S_j(t)$ the percent of new starts at time t which are equipped with solar systems, and $r_j(t)$ is the rate of retrofit, then the instantaneous rate at which the number of new solar-equipped buildings is changing at time t is given by:

$$ns_j(t) = N_j(t) \times c_j(t) \times S_j(t) \qquad (5)$$

and the instantaneous rate at which the number of solar retrofits is changing at time t is given by:

$$ne_j(t) = N_j(t) \times r_j(t). \qquad (6)$$

Thus, the number of new solar-equipped buildings built during the year T will be

$$NST_j(T) = \int_T ns_j(t)\, dt \qquad (7)$$

and the number of solar retrofits during the year will be

$$NET_j(T) = \int_T ne_j(t)\, dt \qquad (8)$$

A simple expression for the number of buildings equipped with solar systems in a given year may be developed by making a few assumptions. Define $G(T_x)$ as a dimensionless areawide growth index for year T_x (relative to year T_o) for the region under study. If the following assumptions are made:

- The demolition rate $d_j(t)$ for all buildings is assumed to remain constant at 2-1/2 percent per year,* i.e., $d_j(t) = d = 0.025$.
- The change in building stock will approximately equal the growth index:

$$\frac{N_j(T_x)}{N_j(T_o)} \cong G(T_x) \qquad (9)$$

---

* As recommended in the GE Phase "0" Report.

- The rate of new construction $c_j(t)$ will be approximately constant over time, i.e., $c_j(t) = c_j$

then the rate of new construction is approximately equal to:

$$c_j = \frac{\ln (G (T_x))}{T_x - T_o} + 0.025 = \text{constant} \qquad (10)$$

and the net rate of building stock change is approximately:

$$P_j = c_j - d = \frac{\ln (G (T_x))}{T_x - T_o} \qquad (11)$$

The average number of total buildings existing T years after base year T_o is then:

$$N_j(T) \simeq N_j(T_o)\ e^{P_j T} \qquad (12)$$

and the average number of new buildings built in year T is given by:

$$\begin{aligned} NS_j(T) &= c_j \times N_j(T) \\ &= c_j \times N_j(T_o)\ e^{P_j T} \qquad (13) \end{aligned}$$

If $S_j(T)$ is the percentage of new buildings which are equipped with solar systems during year T, then the number of buildings equipped with solar systems during the year T[*] is:

$$NST_j(T) = NS_j(T) \times S_j(T) \qquad (14)$$

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[*] Note that the cumulative number of buildings equipped with solar systems by year T_x is then:

$$\sum_{\substack{\text{all } T \\ \leq T_x}} \sum_{j} NST_j(T)$$

(6) Areawide Fuel Savings

The number of new buildings built in year T which are equipped with solar systems is $NST_j(T)$, as defined by equation (14):

$$NST_j(T) = NS_j(T) \times S_j(T) \qquad (14)$$

The potential annual per-building fuel savings (U_{jk}) were defined above in equation (3). The areawide savings of fuel k in residential buildings by year T_x is then:

$$UT_k^r(T_x) = \sum_{\substack{\text{all } T \\ \leq T_x}} \sum_{\substack{j \\ \text{residential}}} (S_j(T) \times NS_j(T) \times U_{jk}) \qquad (15)$$

The areawide savings of fuel k in commercial buildings by year T_x is then:

$$UT_k^c(T_x) = \sum_{\substack{\text{all } T \\ \leq T_x}} \sum_{\substack{j \\ \text{commercial}}} (S_j(T) \times NS_j(T) \times U_{jk}) \qquad (16)$$

The total areawide fuel savings are therefore:

$$UT_k^t(T_x) = UT_k^r(T_x) + UT_k^c(T_x) \qquad (17)$$

These fuel savings can be translated into air pollution emissions that would have been generated had these fuels been burned to satisfy the energy loads that solar systems may supply. Factors affecting changes in these emission levels are discussed in the next section.

2. CHANGES IN POLLUTANT CONCENTRATIONS DUE TO REDUCED FUEL COMBUSTION

As described in the previous section, utilization of solar energy will produce savings of electricity and fossil fuels burned directly for space heating and hot water. The latter will result in reduced residential and commercial source fuel combustion emissions, while the former will result in reduced point source emissions from power plants. Changes in emission rates will produce changes in ambient pollutant concentrations. In the section below the impact on air quality from area source emission changes is discussed. The following section deals with power plant emissions.

(1) Area Source Emissions and Air Quality

The emission inventory of a metropolitan area contains the location and emission levels for the air pollution sources in the area. For purposes of pollutant dispersion modeling, emissions from area sources are represented as emission densities which are uniform over a given grid area. The least accurate representation of area source emissions corresponds to a uniform area source emission density over the entire urban area. The reliability of pollutant concentration estimates increases if the urban area can be divided into a large number of small grids, for which individual emission densities are calculated.

Gridded area source emissions may be calculated in one of two ways:

- Directly from highly detailed source-emission data
- By allocating aggregated emission levels to smaller grid areas.

If detailed fuel use and emission data are available for small gridded areas, the method described in Section 1 of this chapter may be used to estimate the changes to the emission inventory resulting from the utilization of solar energy. The more feasible approach, in terms of data which are ordinarily available, is to use the method described previously to estimate emissions for comparatively large areas, and to allocate emissions to subcounty grids. Several allocation techniques, including both computerized and manual methods, are described in the AQMA Guidelines.*

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* EPA, Guidelines for Air Quality Planning and Analysis, Vol. 8, ("Computer-Assisted Area Source Emissions Gridding Procedure") and Vol. 13 ("Allocating Projected Emissions to Subcounty Areas.")

In either case, the change in emissions for any grid for pollutant p is given by:

$$\Delta E_p^a(T_x) = \sum_k \left(UT_k^r(T_x) \times EF_{pk}^r + UT_k^c(T_x) \times EF_{pk}^c \right) \quad (18)$$

and the change in the emission density for any grid (regardless of grid size) is

$$\Delta Q_p(T_x) = \frac{1}{A} \sum_k \left(UT_k^r(T_x) \times EF_{pk}^r + UT_k^c(T_x) \times EF_{pk}^c \right) \quad (19)$$

when A is the grid area; $UT_k^r(T_x)$ and $UT_k^c(T_x)$ are the residential and commercial fuel savings for fuel k for sources within the grid; EF_{pk}^r and EF_{pk}^c are the residential and commercial emission factors (lb of pollutant p per unit fuel k). Emission factors for the most common residential and commercial fuels are given in Table 17.

Table 17
Emission Factors for Common Residential and Commercial Fuels

Fuel	Pollutant					Units
	TSP	SO_x	NO_x	HC	CO	
Residual Oil						
Residential	10	144 S	12	3	5	$lb/10^3$ gal
Commercial	23	159 S	60	3	4	$lb/10^3$ gal
Distillate Oil						
Residential	10	144 S	12	3	5	$lb/10^3$ gal
Commercial	15	144 S	60	3	4	$lb/10^3$ gal
Natural Gas	19	0.6	100	8	20	$lb/10^6 ft^3$

Note: S is percent sulfur.

The change in area source emission densities described previously will result in changes in expected pollutant concentrations. A number of techniques have been developed to relate pollutant concentrations to atmospheric conditions and background concentrations. The choice of appropriate atmospheric dispersion model depends on the pollutant and averaging times under consideration, the accuracy and detail of the emission inventory, and the availability of meteorological data. Table 18 shows National Ambient Air Quality Standards and the averaging times defined for each criteria pollutant.

Table 18
Federal Ambient Air Quality Standards*

		Maximum Concentration	
Pollutant	**Averaging Time**	**Primary Standard**	**Secondary Standard**
Suspended particulate matter	Annual	75 $\mu g/m^3$	60 $\mu g/m^3$
	24 hr	260 $\mu g/m^3$	150 $\mu g/m^3$
Sulfur oxides	Annual	0.03 ppm	0.02 ppm
	24 hr	0.14 ppm	0.10 ppm
	3 hr		0.5 ppm
Carbon monoxide	8 hr	9 ppm	9 ppm
	1 hr	35 ppm	35 ppm
Photochemical oxidants	1 hr	0.08 ppm	0.08 ppm
Nonmethane hydrocarbons	3 hr (6-9 a.m.)	0.24 ppm	0.24 ppm
Nitrogen oxides	Annual	0.05 ppm	0.05 ppm

Additional standards have been proposed for asbestos, beryllium, mercury, and lead; they are being prepared for fluorides, polycyclic organic compounds, odors (including hydrogen sulfide), chlorine, hydrogen chloride, arsenic, cadmium, copper, manganese, nickel, vandium, zinc, barium, boron, chromium, selenium, pesticides, radioactive substances, and aeroallergens.

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*40 CFR 50; 36 FR 22384, November 25, 1971; as amended by 38 FR 25678, September 14, 1973, and 40 FR 7042, February 18, 1975.

A summary of the dispersion models which are the most widely available to air pollution control agencies is given in Volume 12 of the AQMA Guidelines, "Applying Atmospheric Simulation Models to Air Quality Maintenance Areas." This volume contains information concerning the general nature, data requirements and level of detail of several models. Some of the techniques which may be applied for hand calculation of the area source air quality impacts of solar heating and cooling systems are shown in Table 19. These models are described in more detail below.

Table 19
Selected Atmospheric Dispersion Models
for Area Source Emissions

Pollutant	Applicable Model
Particulates	Hanna-Gifford Rollback
Sulfur oxides	Hanna-Gifford Rollback
Nitrogen oxides	Rollback
Carbon monoxide	Rollback
Hydrocarbon/oxidants	Appendix J Rollback

1. Rollback

The rollback model is based on the following expression relating pollutant concentrations (X) to emission rates (Q) and background concentration (b):

$$X = kQ + b \qquad (20)$$

This method assumes that the dispersion parameter k does not vary with time or with source-receptor relationships, and that emission rates are uniform across the area. Thus the relationship of emissions (Q_t) and air quality in a future year (X_t) to the emissions (Q_o) and air quality (X_o) in a base year can be expressed by the following proportionality:

$$\frac{X_t - b}{X_o - b} = \frac{Q_t}{Q_o} \tag{21}$$

The basic assumption in the model is that a given percent change in pollutant emissions will result in a similar change in pollutant concentrations. It is a technique for scaling concentrations up or down to reflect similar changes in the gross emission rates. The inputs required for this method are areawide emissions for the base year and the year of interest, and a pollutant concentration representative for the area and averaging time of interest.

2. Appendix J HC-O_x Relationship

Appendix J of Federal Register 40 CFR Part 51 contains a graphical presentation of the percent reduction in hydrocarbon (HC) emissions required to reduce an observed peak hourly average oxidant (O_x) concentration to the National Ambient Air Quality Standard (NAAQS) for O_x. The relationship assumes that the maximum 1-hour O_x concentration is directly affected by the quantity of HC emitted during the morning hours. This assumption is based on the observed relationship of HC and O_x concentrations. To use this method, emission levels for the base year and year of interest must be known.

3. Hanna-Gifford Model

This model is most appropriate for stable pollutants such as SO_2, particulates, and CO and may be used to estimate 1-hour and annual average concentrations of these pollutants. The model can be used to estimate an average concentration for any defined area. In the basic Hanna-Gifford model, the dispersion constant is a function of stability, wind speed and the size and number of area sources. The equation relating concentrations to emissions is

$$X = \left(\frac{2}{\pi}\right)^{1/2} \frac{(\Delta L/2)^{1-b}}{a(1-b)U} \left(Q_o + \sum_{i=1}^{N} Q_i \left[(2i+1)^{1-b} - (2i-1)^{1-b}\right]\right) \quad (22)$$

where

- a, b, are empirically determined constants used to specify dispersion; they are functions of the atmospheric stability,
- ΔL is the size (width) of the area sources,
- N is the number of upwind sources
- i is a specific upwind source
- Q_o is the pollutant emissions for the area in which the receptor site is located,
- Q_i are the emissions for upwind areas
- U is the average wind speed for the averaging time of interest.

The model is applied to each subarea within the metropolitan area. The application is made for the wind direction, wind speed and stability class for each meteorological situation under consideration. All sources upwind of the receptor area are included in determining the pollutant impact. This approach may be used to estimate hourly average concentrations for all situations of interest. Concentrations for other averaging times can be obtained by estimating concentrations for each hour of the period and averaging the hourly concentrations.

In those cases where:

- Source strengths Q_i do not differ significantly from source strength Q_o

- The grid areas are relatively large (county size),

it has been shown that the Hanna-Gifford equation for the change in concentration simplifies to:

$$\Delta X = C\frac{\Delta Q}{\overline{U}} \qquad (23)$$

where $\overline{U}$ is annual average wind speed and ΔQ is the change in the average emission density (g/sec-m^2) for each area. Values for the constant C, which is dependent on the pollutant, may be determined empirically from observed data.

* * * * *

Any one of the techniques summarized above would be implemented in a similar manner. The model developed in the previous section may be used to estimate changes in emission densities. For the rollback or Appendix J methods, the change in the emission density for the entire metropolitan area should be calculated. For the Hanna-Gifford method, the change in the emission density of subareas is required; the smallest subarea for which building counts are readily available is ordinarily the county level.

An accurate estimation of 1, 3, 8 or 24 hour averages for any pollutant requires more than annual average emission rates. Hourly emission rates are usually used, and added to form emission rates for longer periods. If emission rates for the shorter time periods are not available, the only alternative is to allocate annual emissions to smaller time periods, thus assuming that hour-to-hour variations in emission rates will not have a significant effect on estimated pollutant concentrations.

The approach described above, which involves allocating annual fuel savings from solar systems uniformly to smaller time periods, will not produce a true representation of actual hourly or daily emission rates.

It is clear that residential and commercial space conditioning fuel use varies seasonally, diurnally, and is affected by unusual climatic conditions. The hot water load in any building depends on the use patterns of the occupants.

(2) Air Quality Impacts Due to Reduced Demand For Electricity

Electricity provides a significant portion of the residential and commercial space conditioning and hot water load. Many domestic hot water heaters and most residential air conditioning systems are electric. Because of natural gas curtailments, many new buildings are equipped with electric space heat. Solar systems, especially when installed in new buildings, will result in savings of electricity.

The question of how solar-induced electricity savings will impact air quality in an urban area is a complex one. A change in the emission levels due to power generation will occur if solar systems reduce peak electrical demand, or if widespread use of solar systems reduces the need for new generating capacity. These two considerations are discussed in more detail below.

Whether solar systems will reduce peak demand depends on the operating characteristics of the utility and the patterns of solar energy utilization. The latter, as discussed previously, depends on climate (outdoor temperature, humidity and wind) and the duration of periods of sunshine.

The following examples illustrate the potential impacts which different applications of solar energy can have on a utility load:

- In some cold climates, winter peak demands tend to occur during overcast periods, and, as a consequence, the conventional heating/cooling system, which is required as an auxiliary in almost all solar system applications, would likely be required simultaneously with the utility's peak load, thus aggrevating the requirement for peaking capacity. Although this situation could conceivably be avoided by installation of a large storage system which was maintained at an elevated temperature, even during overcast periods, by use of the auxiliary system at off-peak hours, the potential requirement for peaking capacity would remain unless the utility were able to control the auxiliary system directly.

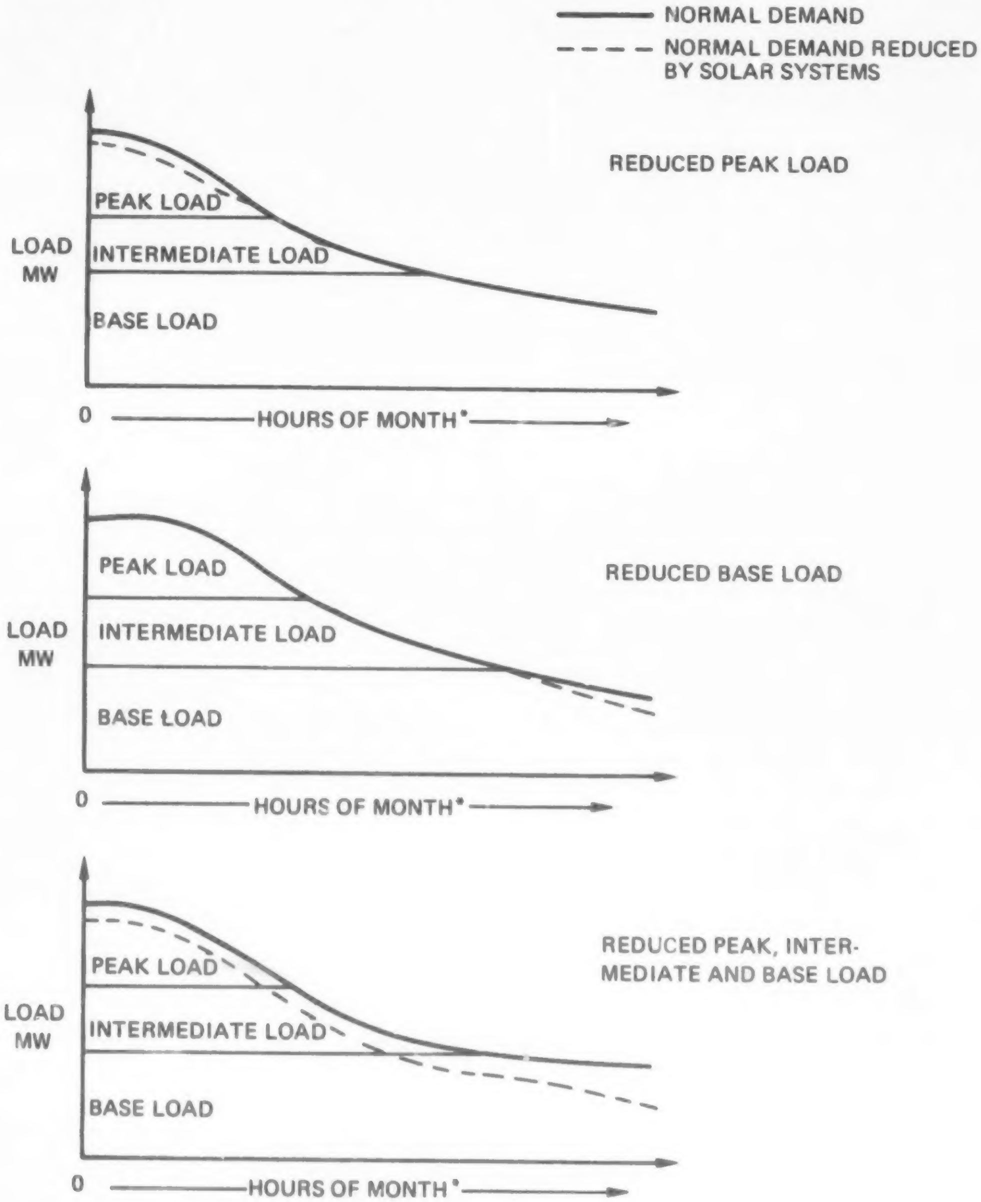
- In a warm climate the utility will likely have a summer peak. Peak cooling loads might tend to be significantly reduced by application of solar energy in areas where the hottest days, as well as the hottest periods of the day, correspond closely to the times when the sun shines brightest.
- Hot water energy requirements are usually less than 10 percent of the total residential and commercial energy demand. While hot water requirements alone will probably not be large enough to affect peak electrical demand significantly, they may have a contributory effect. Peak domestic hot water loads usually occur in the mornings and evenings, while commercial hot water loads peak at different times depending on the type of establishment.

Whether solar systems reduce peak demand will depend, therefore, on characteristics unique to each urban area. Typical monthly load duration profiles characterizing utility operations are shown in Figure 8. Three hypothetical cases involving solar systems applications are shown in the figure. In the first case, solar energy reduces peak demand. In the second case, the base load is affected, and in the third, both the peak and base load are reduced.

A change in peak electrical demand has a direct air quality impact. Peaking units are brought on line to supplement base generating capacity at times of peak demand. In many cases peaking units are the oldest and least efficient units in the system, or are gas turbines fired with distillate oil. In many cities the older generating stations are located in the urban area rather than in surrounding rural areas. Thus reducing peak demand will often result in a decrease in power plant emissions in the downtown area, the most critical area from an air quality standpoint. This will be true even if the reduction in peak demand is occasional and not long term.

A change in base electrical load will not have as direct an impact on air quality. First of all, the base

FIGURE 8
Possible Impact of Solar Energy Utilization on Load Duration Profiles



*The number of hours in a month for which the load was greater than or equal to the ordinate value.

load reduction must be substantial in order to reduce the amount of spinning capacity on line. The reduction must also be long term and not an irregular occurrence, such as a daily or seasonal fluctuation in electrical demand. A long term, substantial change in base load would most likely impact the construction of new generating units. This is because any change in base load would occur gradually, over a long period of time. If the new generating capacity in question were fossil-fueled, there would be a resulting air quality impact. If the new capacity were nuclear, however, other environmental considerations, including risk of radioactive material release and disposal of radioactive wastes, would be involved.

One critical aspect concerning a potential reduction in base load capacity, as mentioned above, is that, in general terms, the system demand must be decreased by an amount equal to the full capacity of a specified generating unit before that unit can be taken off line. It is possible that solar energy systems alone may not cause this much of a reduction. Energy conservation strategies, such as improved insulation and adoption of lower illumination levels, and computerized temperature controls, can also contribute to reducing base load. It is important when electrical base and peak loads are analyzed, that the combined effect of all supply and demand strategies be included in the analysis, even though individually the strategies may not have significant impact.

In the event that solar energy utilization does contribute to a reduction in the rate of electricity generation, particulates, sulfur oxides and nitrogen oxides are the criteria pollutants for which emission levels would be most significantly affected. Table 20 shows nationwide 1972 emission levels for the criteria pollutants. Referring to the table, generation of electricity for residential and commercial use produced a substantial portion of TSP (9.4 percent), SO_x (29 percent), and NO_x (13.1 percent) emissions on a nationwide basis.

In many metropolitan areas, the major sources of TSP and SO_x emissions are stationary fuel combustion and industrial process facilities. Urban areas which contain several electricity generation stations, and comparatively little heavy industry, would be the areas for which reduced electricity demand resulting from

Table 20
Nationwide Emission Levels (1972)

	Emissions (1,000 Tons Per Year)				
Emission Sources	**TSP**	**SO_x**	**NO_x**	**HC**	**CO**
Electricity Generation					
Residential use only	1,083	5,564	1,882	23	75
Commercial use only	779	4,000	1,353	17	54
Total (all users)	3,385	17,388	5,881	72	235
Mobile Sources	774	625	8,721	16,279	77,418
Grand Total	19,790	33,208	24,642	27,791	107,303
All Point Sources	15,018	28,902	14,091	6,969	19,037
All Area Sources	4,772	4,306	10,551	20,822	88,266

Sources: Emission data: EPA, *1972 National Emissions Report* (June 1974).

Distribution of electricity generation emissions: "Twenty-sixth Annual Electrical Industry Forecast," *Electrical World*, September 15, 1975 (contains electrical usage for 1972: residential [32%] commercial [23%] of total). Emissions from electricity generation were allocated to residential and commercial applications by assuming that emissions for all pollutants are proportional to electricity usage.

solar energy utilization would have the greatest potential impact on TSP and SO_x (including fine particulates and sulfates) concentrations.

As indicated in Table 20, almost half of the NO_x emissions nationwide were caused by mobile sources, primarily automobiles. In most urban areas, therefore, where automobile use is heaviest, solar energy utilization would probably not affect NO_x concentrations to a significant extent.

Standard procedures for estimating the changes in pollutant concentrations due to changes in point source emission rates require definition of the following:

- Meteorological data (wind speed and direction, atmospheric stability and mixing height)
- Location of the plant
- Stack parameters (height, diameter, exit temperature and exit velocity)
- Hourly emission rates.

The last two parameters above depend on which generating unit or units at the plant are affected and the fuels burned by those units. Most point source dispersion models use the standard Gaussian diffusion equation to predict long-term pollutant concentrations from the above data.

A generalized assessment of the air pollution impact of solar systems may be made without detailed point source dispersion modeling. This approach involves estimating only the areawide power plant emission reduction (in tons per year) which corresponds to expected electricity savings. The methodology presented in the previous section defined the areawide fuel savings for electricity in year T_x as $UT^t_{k'}(T_x)$ (for the subscript k' corresponding to electricity. The subscript k referred previously to the type of end-use fuel consumption and is omitted below since the only end-use fuel savings considered is electricity. The subscript k is used below for the type of fuel burned at a power plant. Using the notation of the preceding section, define $FFC_k(T_x)$ as the fraction of the total electricity savings corresponding to power plant fuel k*. Also define CE_k as the conversion efficiency for fuel k, defined as (kWh of delivered electricity)/(unit of fuel input†). The term CE_k thus includes generation and transmission losses. If EF_{pk}

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* Thus $\sum_k FFC_k(T_x) = 1.0$

† Such as tons of coal, gallons of oil, etc.

are the emission factors (pounds of pollutant per unit fuel k), then the emission reduction for pollutant p is given by:

$$\Delta E_p^e(T_x) = \sum_k UT_{k'}^t(T_x) \times FFC_k \times EF_{pk}^e/CE_k \qquad (24)$$

Note that $UT^t(T_x)$ above must be expressed in kWh/yr. Emission factors for the most common power plant fuels, EF_{pk}^e, are given in Table 21. Typical values for generating conversion efficiencies CE_k are given in Table 22.

In summary, therefore, the potential air quality impacts due to reduced demand for electricity depend on the manner in which patterns of solar energy utilization affect daily and monthly load profiles of the electric utility in the urban area. To define this impact with any degree of accuracy, a careful analysis of all pertinent factors which are unique to that region must be performed, as they have been earlier in this section, to determine source emission reductions from buildings. Several of the factors that might be considered in this analysis include the following:

- The existing source of electrical power for the region. Displacement of coal burning plants offers a larger potential for reduced emissions than do low-sulfur oil- or gas-fired units.

- The location of the existing generating capacity. The location being analyzed (e.g., a countywide region) may, in fact, have no power plants within its borders. In this case, any changes in the regional load profile due to solar market penetration will impact air quality most directly in the region containing the power plant.

- How anticipated acceptance of solar heating and cooling systems will modify current load profiles. As stressed earlier, the effect on the peak, intermediate and base load profile characteristics must be defined before explicit analyses of impacts can be carried out.

Table 21
Emission Factors For Common Power Plant Fuels (EF^{e}_{pk})

	Pollutant (p)					
Fuel (k)	TSP	SO_x	NO_x	HC	CO	Units
Bituminous Coal	2.2A	38 S	20	.3	1	lb/ton
Residual Oil	8	159 S	105	2	3	lb/10^3 gal
Distillate Oil	8	144 S	105	2	3	lb/10^3 gal
Natural Gas	15	0.6	600	1	17	lb/10^6 ft^3

Note: S is percent sulfur
A is percent ash

Source: EPA, *Compilation of Air Pollutant Emission Factors* (document AP-42), April 1973.

Table 22
Typical Conversion Efficiencies For Power Plants (CE_k)*

Fuel (k)	Btu content per unit fuel	CE_k 1000 kWh/unit fuel	Unit fuel
Bituminous Coal	26.2×10^6	2.3	ton
Residual Oil	150×10^6	13.2	1000 gal
Distillate Oil	134×10^6	12.2	1000 gal
Natural Gas	10^9	87.9	10^6 cu. ft.

Note: Assumes 33% thermal efficiency and 8% transmission loss (11,373 Btu burned/kWh delivered).

*Includes generating and transmission losses.

Once changes in load profiles are forecast, it can be determined if the resulting reduced demand may be satisfied by reducing the number of units already on line (which will reduce emission density in the region) or by lowering load growth projections and delaying construction of new capacity.

3. SUMMARY OF THE METHODOLOGY

The methodology described in the previous two sections for estimating the annual fuel savings due to solar heating and cooling systems may be summarized as follows:

- T_x is the year for which the methodology is used to calculate annual fuel savings
- T_o is the base year to which areawide growth is referenced
- Subscripts:
  - j = building type
  - k = fuel
  - m = application (heating, cooling, hot water)
- Input data:
  - $G(T_x)$ is the growth index for the region referenced to base year T_o
  - FFN_{jkm} are the fuel use factors for new buildings (percent of all new buildings using fuel k for application m)
  - S(T) is the parameter defining the rate of market penetration of solar systems (percent of new buildings which are equipped with solar systems in year T), assumed to be the same for all building types j
  - $N_j(T_o)$ is the building stock of type j in the base year T_o.

The key equations of the methodology are:

(1) Solar-related energy savings (Btu) per building (equation 1):

$$E_{jm} = B_{jm} \times F_{jm}$$

Typical values for B_{jm} are given in Tables 12 and 13; typical values for F_{jm} are given in Tables 14 and 15.

(2) Potential fuel savings per building (equation 3):

$$U_{jk} = \frac{1}{c_k} \sum_{m} (FFN_{jkm} \times E_{jm}/HE_{km})$$

Typical values for HE_{km} are given in Table 16.

(3) Annual rate of construction of new buildings (equation 10):

$$c_j = \frac{\ln(G(T_x))}{T_x - T_o} + 0.025$$

(4) Annual net rate of building stock change (equation 11):

$$P_j = \frac{\ln(G(T_x))}{T_x - T_o}$$

(5) Average number of new buildings built in year T (equation 13):

$$NS_j(T) = c_j \times N_j(T_o)\, e^{P_j(T-T_o)} \quad (T \le T_x)$$

(6) Areawide residential fuel savings by year T_x (equation 14):

$$UT_k^r(T_x) = \sum_{\text{all } T \leq T_x} \left[S(T) \sum_{\substack{j \\ \text{residential}}} \left(NS_j(T) \times U_{jk} \right) \right]$$

(7) Areawide commercial fuel savings by year T_x (equation 15):

$$UT_k^c(T_x) = \sum_{\text{all } T \leq T_x} \left[S(T) \sum_{\substack{j \\ \text{commercial}}} \left(NS_j(T) \times U_{jk} \right) \right]$$

(8) Total areawide fuel savings (equation 16):

$$UT_k^t(T_x) = UT_k^r(T_x) + UT_k^c(T_x)$$

(9) Change in annual areawide (area source) emissions due to reduced on-site fuel combustion (equation 18):

$$\Delta E_p^a(T_x) = \sum_k \left[UT_k^r(T_x) \times EF_{pk}^r + UT_k^c(T_x) \times EF_{pk}^c \right]$$

(only for on-site fuels k)

Typical values for EF_{pk}^r and EF_{pk}^c are given in Table 17.

(10) Change in annual areawide emissions due to reduced power plant fuel combustion (equation 24):

$$\Delta E_p^e(T_x) = \sum_k \left[UT_{k'}^t(T_x) \times FFC_k \times EF_{pk}^e / CE_x \right]$$

(only for electricity savings k')

Typical values for EF_{pk}^e are given in Table 21; typical values for CE_k are given in Table 22.

4. SAMPLE APPLICATION OF THE METHODOLOGY

This section illustrates how the methodology developed in the preceding sections can be applied to forecast the changes in emission and air quality levels in any urban area due to utilization of solar technology for heating and cooling residential and commercial buildings. For the purposes of this example, several assumptions were made concerning the input data required in order to expedite the analysis. Therefore, the numerical results presented should not be considered an accurate forecast of air quality impacts in the metropolitan area studied.

The geographic region, type of housing, and timeframe selected for this example were:

- Geographic region: Baltimore, Maryland SMSA
- Type of building: residential, single-family ($j=1$)
- Projected timeframe: to the year 2000.

It should be emphasized that though only residential, single-family homes are considered in this example, a complete analysis must include all building types existing in the geographic region under investigation.

The values for subscripts used in this example are identified below:

Subscript	Identification
j	Building Type 1 - residential, single-family
k	Building Fuel 1 - distillate oil 2 - natural gas 3 - electricity
m	Application 1 - space heating 2 - space cooling 3 - water heating

To determine the change in emissions in a particular region, the following must be calculated:

- The energy demand for single-family residences in the region
- Potential energy savings per building
- Potential fuel savings per building
- A forecast of the number of residences equipped with solar systems
- Areawide residential fuel savings
- The expected change in emission density.

(1) Energy Demand for Single Family Residences in the Region

Typical values for B_{jm} (expressed in Btu/year) are given in Table 12 for space heating and cooling. Values are given for cities in the different climatic regions of the county. Table 13 contains typical water heating loads. These values are summarized below for single-family residential houses in the Baltimore area:

Application	Building Energy Demand, B_{jm} (Btu/year)
Space Heating (B_{11})	112×10^6
Space Cooling (B_{12})	33×10^6
Water Heating (B_{13})	13.3×10^6

(2) Potential Energy Savings Per Building

Energy savings (Btu) per building are given by equation (1):

$$E_{jm}\ (\text{Btu}) = B_{jm} \times F_{jm} ,$$

where F_{jm} is that portion of the energy load that can be satisfied by solar systems. Typical values for F_{jm} are given for cities in the different climatic regions of the country in Tables 14 and 15. The values for Washington, D.C., in those tables were used in this example:

Application	F_{jm}: Portion of Energy Demand Satisfied By Solar Systems ($j=1$)
Space Heating (F_{11})	0.46
Space Cooling (F_{12})	0.72
Water Heating (F_{13})	0.90

Applying these values in equation (1), the energy demand satisfied by solar systems in single-family houses is calculated to be:

$$E_1 = \sum_m E_{1m} = (B_{11})\times(F_{11}) + (B_{12})\times(F_{12}) + (B_{13})\times(F_{13})$$

$$= [(112)\times(0.46) + (33)\times(0.72) + (13.27)\times(0.9)]\ 10^6$$

$$= 87.22\text{x}10^6 \text{ Btu/yr}$$

This is composed of:

- $E_{11} = 51.52\text{x}10^6$ Btu/yr for space heating load saved
- $E_{12} = 23.76\text{x}10^6$ Btu/yr for space cooling load saved
- $E_{13} = 11.94\text{x}10^6$ Btu/yr for water heating load saved.

(3) Potential Fuel Savings Per Building

The annual fuel savings possible in each type of building is a function of the energy saved by using solar systems (E_{jm}), the percent of each type of fuel used by these buildings to generate this energy level (FFN_{jkm}), and the efficiency expected from using these different fuelstocks (HE_{km}). The relationship for per-building fuel savings is given by equation (3):

$$U_{jk} = \frac{1}{c_k} \sum_m (FFN_{jkm} \times E_{jm}/HE_{km})$$

where:

c_k = the energy per unit of fuel (e.g., Btu/gallon of oil);

FFN_{jkm} = portion of buildings using each type of fuel;

HE_{km} = the ratio of energy delivered or removed to energy supplied for each type of fuel.

Typical values for HE_{jm} were given in Table 16. Values for FFN_{jkm} used in this example are shown in Table 23. These values are for new residential

Table 23
Fuel Use Factors, FFN_{jkm}*

Fuel or Energy Source	Application (m=1) Space Heating	(m=2) Space Cooling	(m=3) Hot Water Heating
Heating Oil (k=1)	0.60	0.00	0.00
Natural Gas (k=2)	0.00	0.00	0.00
Electricity (k=3)	0.40	1.00	1.00

* Source: EPA, *Development of a Trial Air Quality Maintenance Plan Using the Baltimore Air Quality Control Region*, September 1974.

construction only. For this example it was assumed that electricity will supply the space heating requirements for 40 percent of the new homes, as well as all air conditioning and water heating energy requirements. It is assumed that oil will satisfy the balance of the residential heating load requirements with natural gas (due to continued curtailment of this fuel), coal and other fuels (e.g., wood, propane, etc.) not used for new homes. For this example, the value of U_{jk} are given as follows using equation (3):

$$U_{11} = \frac{1}{c_1}\left[\left(\frac{1}{0.60}\right)\left(51.52\text{x}10^6\right)\ (0.6)\right]$$

$$= \frac{1}{c_1}\left(51.52\text{x}10^6\right)\ \text{Btu/yr}$$

$$U_{12} = \frac{1}{c_2}\left[\frac{1}{0.65}\left(51.52\text{x}10^6\right)\ (0)\right.$$

$$+ \left(\frac{1}{0.60}\right)\left(23.76\text{x}10^6\right)\ (0)$$

$$\left. + \left(\frac{1}{0.60}\right)\left(11.94\text{x}10^6\right)\ (0)\right] = 0$$

$$U_{13} = \frac{1}{c_3}\left[\left(\frac{1}{1.00}\right)\left(51.52\text{x}10^6\right)\left(0.40\right)\right.$$

$$+ \left(\frac{1}{2.5}\right)\left(23.76\text{x}10^6\right)\ \left(1.00\right)$$

$$\left. + \left(\frac{1}{0.60}\right)\left(11.94\text{x}10^6\right)\ \left(1.00\right)\right]$$

$$= \frac{1}{c_3}\left(50.01\text{x}10^6\right)\ \text{Btu/yr.}$$

For heating oil, c_1 = 144,000 Btu/gal, and for electricity, c_3 = 3412 Btu/kWh; therefore, for residential, single-family homes in the Baltimore SMSA, the potential per-building fuel savings are:

- $U_{11} = 51.52 \times 10^6$ Btu/yr = 358 gal of heating oil/yr
- $U_{12} = 0$
- $U_{13} = 50.01 \times 10^6$ Btu/yr = 14.66×10^3 kWh/yr.

(4) Forecast of the Number of Residences Equipped With Solar Systems

The number and types of buildings in a region is an important statistic that is used as a base upon which the per-building energy savings resulting from solar system applications can be obtained. Inherent in this analysis is the assumption that solar systems will not be retrofitted in existing structures due to high cost but will be applied exclusively in new construction.

The following data were used in this example:

- T_x = forecast target year = 2000
- T_o = base year = 1975
- $N_1(T_o)$ = 455,984 (the number of residential, single family dwellings in the Baltimore SMSA)*
- $G(T_x)$ = 1.184 (the areawide growth index for the year 2000, referenced to 1975).

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* Excludes mobile homes and trailers. Source: 1970 Census of Housing—Maryland.

Based on population growth projections for Baltimore SMSA. Source: OBERS Projections, Population Series, U.S. Water Resources Council, April 1974. For this example, the building growth rate is assumed to be the same as the projected growth rate for the population in the region (a statistic easily obtainable). A more thorough analysis, however, must either verify this relationship or obtain a more accurate indication of $G(T_x)$.

The annual rate of new construction for residential buildings (j=1) is given by equation (10):

$$c_1 = \frac{\ln G(T_x)}{T_x - T_o} + 0.025 = 0.0318.$$

The net rate of exchange in the building stock is given by equation (11):

$$P_1 = c_1 - 0.025 = 0.00676.$$

The average number of new houses built in year T is given by equation (13):

$$NS_1(T) = c_1 \times N_1(T_o)\ e^{p(T-T_o)}$$

In this example, the number of new houses (j=1 only) built at the midpoint of each five year period between 1975 and 2000 was calculated and used as an annual estimate for each year in that period. The average number of new single-family buildings built during each of the years period between 1975 and 1980 is (from equation 13):

$$0.0318 \times (455{,}984)\ e^{(.00676)2.5} = 14{,}727 \text{ houses per year.}$$

Since this number represents the average new construction during the five year period, the total new construction between 1975 and 1980 is:

14,727 buildings/yr x 5 yrs = 73,634 new buildings.

New construction for each of the other 5-year periods is calculated in a similar manner and the results are presented in Table 24.

(5) Areawide Residential Fuel Savings

The fuel savings during the year 2000 in a metropolitan area for single-family residences is given by equation (11) with j=1:

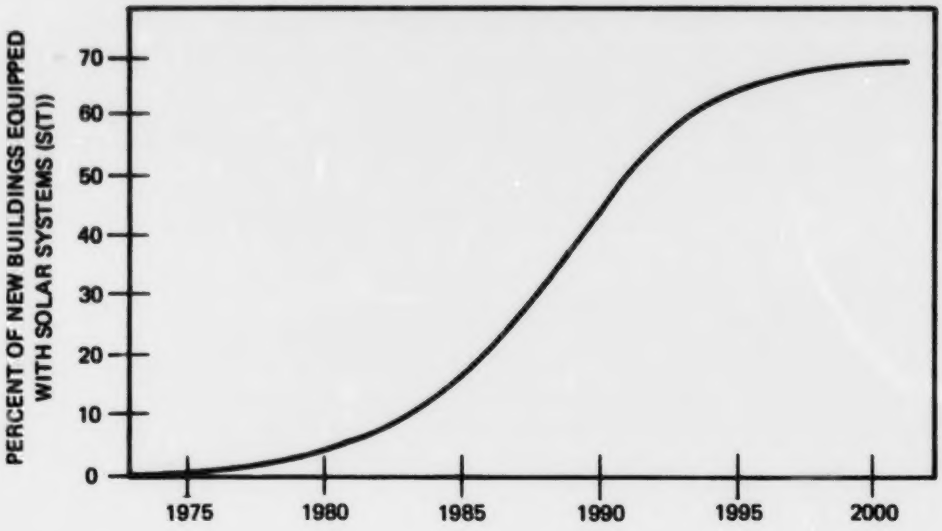
$$UT_k^r(T_x) = U_{1k} \sum_{\substack{\text{all } T \\ \le T_x}} S(T) \times NS_1(T)$$

Table 24
Projected Number of Single-Family Dwellings to be Built to Year 2000 in Baltimore SMSA

Period (Year)	Average Annual Construction (Bldgs/Yr)	Total New Construction (Bldgs)
1975-1980	14,727	73,634
1980-1985	15,233	76,165
1985-1990	15,757	78,784
1990-1995	16,298	81,492
1995-2000	16,859	84,294
	Total New Construction (1975-2000) :	394,369

where T_x is the year 2000. The per-building fuel savings, U_{1k}, and the average number of new homes built in each year T, NS_1 (T), were calculated earlier in this section.

The rate of market penetration of solar systems, S(T), which was used for this example is shown in Figure 9. The rate of solar system acceptance is the parametric input for the mathematical model developed previously in section 1. The values for S(T) in Figure 9 reflect a maximum market capture of 70 percent, and a capture rate which approximates the normal (Gaussian) cumulative distribution function with $\pm 3\sigma$ at 1975 and 2000.



Assumptions:

Market capture limit is 70%. Capture rate approximates the normal cumulative distribution function with ±3σ at 1975 and 2000.

FIGURE 9
Assumed Solar Market Capture (S(T))

The following data may be used to evaluate equation (11):

Time Period (T)	S(T)
1975-1980	0.0056
1980-1985	0.0805
1985-1990	0.3500
1990-1995	0.6195
1995-2000	0.6993

Time Period	S(T)	NS(T)	$\sum(S(T) \times NS(T))$
1975-1980	0.0056	73,634	412
1980-1985	0.0805	76,165	6,131
1985-1990	0.3500	78,784	27,574
1990-1995	0.6195	81,492	50,484
1995-2000	0.6993	84,294	58,948
			143,549 buildings by 2000

The per-building fuel savings, U_{1k} were calculated previously as 358 gallons of oil and 14.66×10^3 kWh per year. Therefore, the residential fuel savings in the year 2000 will be:

- 143,549 x 358 gal/yr = 51.4 million gallons of heating oil
- $143{,}549 \times 14.66 \times 10^3$ kWh/yr = 2.1×10^9 kWh

(6) The Change in Areawide Emissions

The change in area source emissions in the Baltimore area is given by equation (18):

$$\Delta E_p^a(T_x) = \sum_k \left[UT_k^r(T_x) \times EF_{pk}^r + UT_k^c(T_x) \times EF_{pk}^c \right]$$

Since only single-family residences are considered in this example, and since the previous analysis indicated that the only area source fuel savings (UT_k^r or UT_k^c) will be distillate oil (fuel is subscript k), the above equation simplifies to:

$$\Delta E_p^a(T_x) = UT^r(T_x) \times EF_p^r$$

This expression is evaluated in Table 25 below:

Table 25
Calculation of Area Source Emission Reductions

$UT_k^r(Tx)$	Pollutant p	EF_{pk}^r*	Δ Ep(Tx) tons/yr
51.4×10^6 gal/yr	TSP	10	257
51.4×10^6 gal/yr	SO_x	43.2	1110
51.4×10^6 gal/yr	NO_x	12	308
51.4×10^6 gal/yr	HC	3	77.1
51.4×10^6 gal/yr	CO	5	128.5

*Emission factors for distilled oil are from Table 17; units are lb/10^3 gal. Emission factor for SO_x is 144 S where S (percent sulfur) for Baltimore is assumed to be 0.3.

The change in areawide emission levels due to displacement of power plant coal use by solar heating and cooling systems is given by equation (24):

$$\Delta E_p^e(T_x) = \sum_k UT_k^t(T_x) \text{ x } FFC_k \text{ x } EF_{pk}^e/CE_k$$

when $UT_k^t(T_x)$ is $7.165 \text{ x } 10^{12}$ Btu/yr. (this term must be expressed in Btu and corresponds to an end-use electricity savings of $2.1 \text{ x } 10^9$ kWh/yr). Since in this example bituminous coal is the only power plant fuel saved ($FFC_k = 1$), the above equation simplifies to:

$$\Delta E_p^e(T_x) = UT_k^t(T_x) \text{ x } EF_{pk}^e\ /CE_k \text{ (k = coal only).}$$

This expression is evaluated and the results presented in Table 26 below:

Table 26
Calculation of Power Plant Emission Reductions

UT^t (Tx)	Pollutant p	EF^e_{pk}*	CE_k†	Δ Ep(Tx), tons/yr
$2.1 \text{ x } 10^4$ kWh/yr	TSP	22	2.3	10,043
$2.1 \text{ x } 10^4$ kWh/yr	SO_x	38		17,348
$2.1 \text{ x } 10^4$ kWh/yr	NO_x	20		9,130
$2.1 \text{ x } 10^4$ kWh/yr	HC	0.3		137
$2.1 \text{ x } 10^4$ kWh/yr	CO	1.0		457

*Emission factors are from Table III-12; units are lb/ton. Emission factor for TSP is 2.2 A where A (percent ash) for Baltimore is assumed to be 10. Emission factor for SO_x is 38 S where S (percent sulfur) for Baltimore is assumed to be 1.0.

†Generating conversion efficiency is from Table 22, in 1000 kWh/ton of coal.

The total estimated change in areawide emissions is the sum of the area source emission savings ΔE^a (on-site fuel combustion) and power plant emission savings ΔE^e. In Figure 10, total areawide emission savings are compared to 1972 areawide emission levels for Baltimore. The estimates of emission savings are based on several assumptions concerning market penetration and fuel savings. These estimates illustrate the order of magnitude of the potential air pollution impact, using 1972 emission levels as the baseline for the comparison.

* * * * *

5. PARAMETRIC ANALYSIS OF REGIONAL EMISSION SAVINGS

One key feature of the methodology for forecasting changes in annual emissions described in this chapter is that it can be used for parametric analyses. In this section this feature of the methodology is demonstrated by:

- Using the Baltimore data given in the previous section to describe fuel use and emission characteristics of a hypothetical city
- Simplifying the equations to express emission changes as a direct function of one parameter (rate of market penetration)
- Using the simplified equations to develop emission forecasts which correspond to several assumed market penetration rates.

Solar related energy savings per building are given by equation (1):

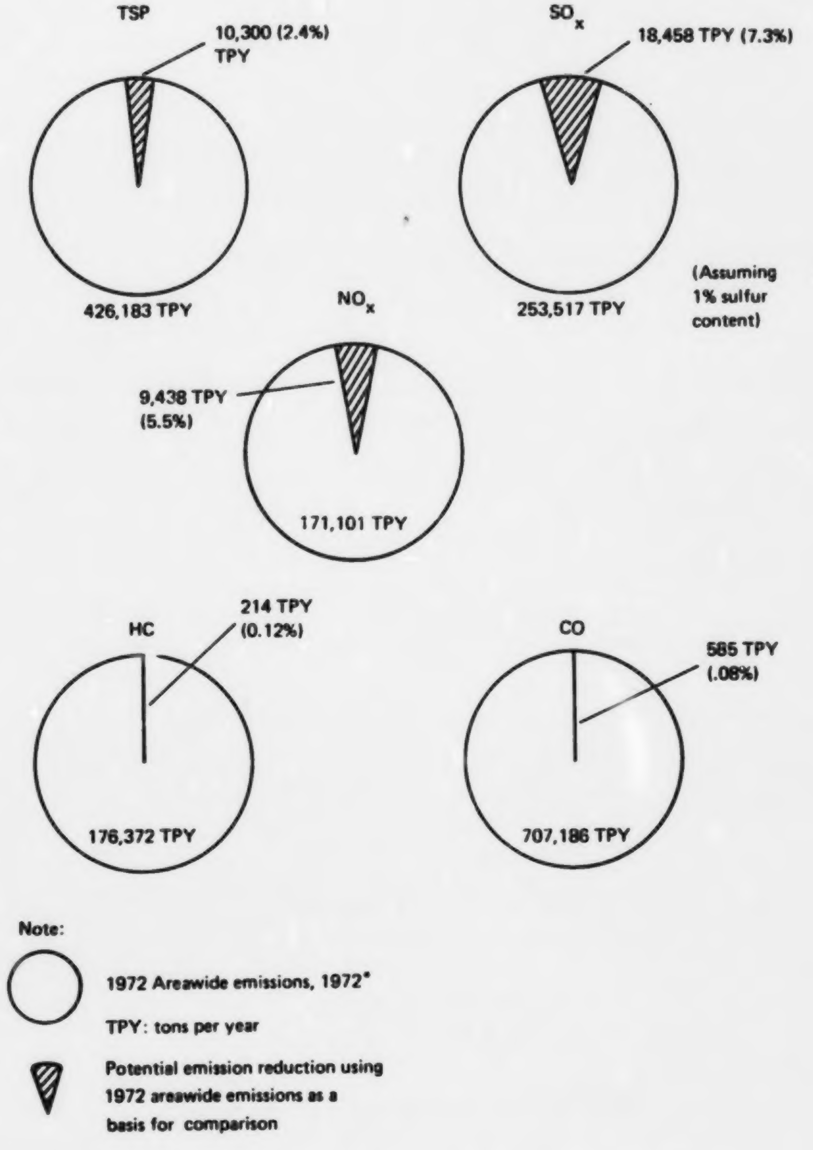
$$E_{jm} = B_{jm} \times F_{jm}$$

Potential per-building fuel savings are given by equation (3):

$$U_{jk} = \frac{1}{C_k} \sum_{m} \left(FFN_{jkm} \times E_{jm} / HE_{km} \right)$$

If it is assumed that solar systems will be installed only in new buildings, and that the only fuel savings will be coal

FIGURE 10
Potential Emission Reductions in Baltimore Associated with the Use of Solar Heating/ Cooling Systems in Single-Family Dwellings in the Year 2000, Compared to Total 1972 Emissions in Baltimore



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*EPA, 1972 National Emissions Report (June 1974)

These potential emission reductions are based on a postulated rate of solar market penetration and future areawide fuel distribution.

This comparison is made only to show the relationship between the magnitude of potential emission reductions in the year 2000 and the magnitude of emission levels in 1972. It is *not* meant to imply solar systems could reduce by 7% the total SO$_x$ emissions in the year 2000.

used to generate electricity (subscript k above is constant) then per building energy savings can be expressed as:

$$U_j = \sum_m B_{jm} \times F_{jm}/HE_m$$

since $FFN_{jm} = 1.0$ for all j and m. Evaluation of this expression gives a constant value for each U_{jk}, i.e., a matrix of constants U_{jk}.

The total areawide fuel savings by year T_x (using equations 13 through 16) is:

$$UT_k^t(T_x) = \sum_{\substack{\text{all } T \\ \le T_x}} S(T) \sum_j \left(c_j \times U_{jk} \times N_j(T_o)\, e^{P_j(T-T_o)}\right)$$

The annual rate of construction c_j, and the annual net rate of building stock change P_j were calculated in the previous section as 0.0318 and 0.00676 respectively (constant for all j). If it is assumed that the parametric input S(T) is constant over time (the same rate of acceptance each year), the above equation may be written as:

$$UT_k^t(T_x) = \underbrace{S(T_x)}_{\text{parametric input}} \times \underbrace{\left(\sum_{\substack{\text{all } T \\ \le T_x}} e^{P_j(T-T_o)}\right)}_{\text{constants}} \times \underbrace{c_j}_{\text{constants}} \times \underbrace{\sum_j}_{\text{constants}} \underbrace{\left(U_j \times N_j(T_o)\right)}_{\text{building stock in the base year}}$$

The change in power plant emissions due to fuel savings $UT_k^t(T_x)$ is given by equation (24):

$$\Delta E_p^e(T_x) = \sum_k UT^t(T_x) \times EF_{pk}^e/CE_k$$

If it is assumed that the only power plant fuel savings will be coal (therefore subscript k above for power plant fuel will be constant), then the change in power plant emissions is:

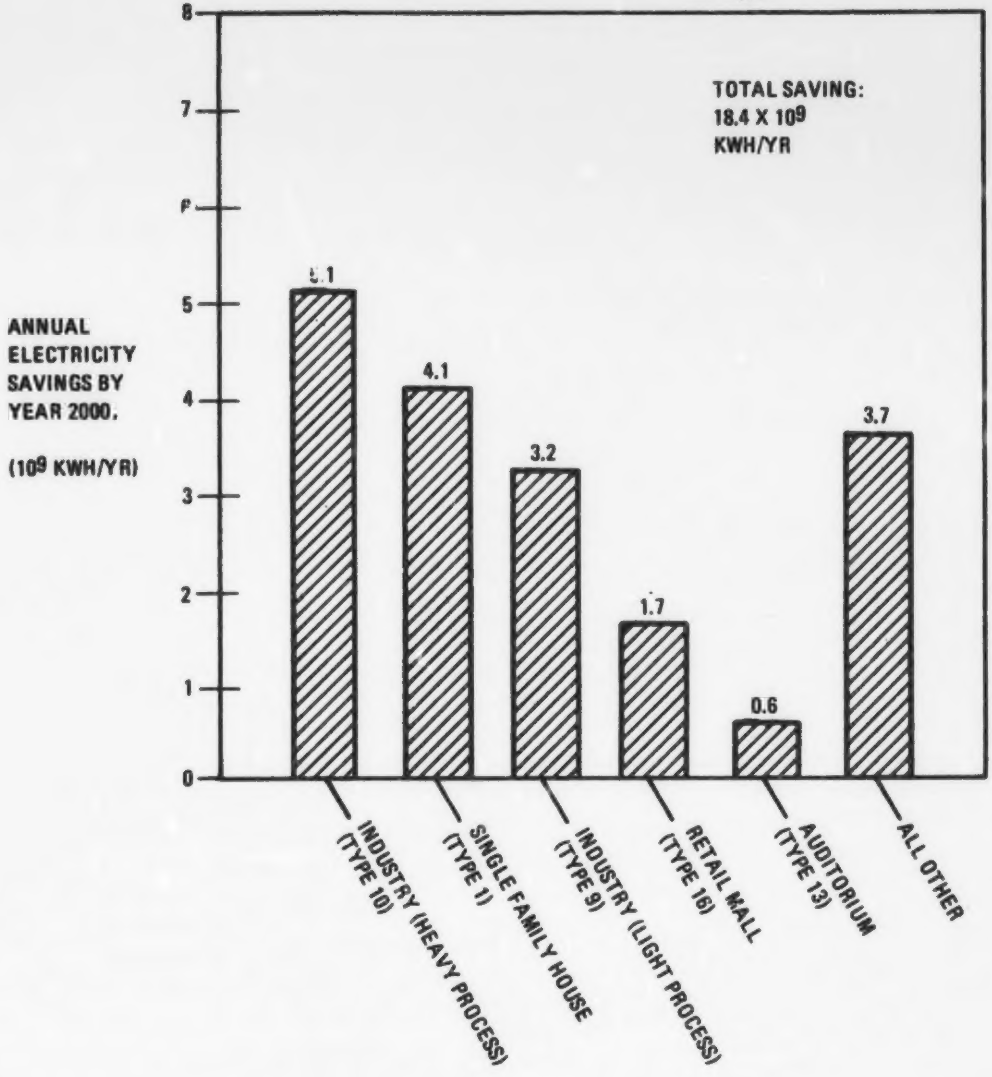
$$\Delta E_p^e(T_x) = \underbrace{S(T)}_{\text{parametric input}} \times \underbrace{\left(\sum_{\substack{\text{all } T \\ \leq T_x}} e^{P_j (T-T_o)} \right)}_{\text{constants}} \times \underbrace{c_j}_{\text{constants}} \times \underbrace{\sum_j}_{\text{constants}} \Big(U_j \times \underbrace{N_j(T_o)}_{\text{building stock in the base year}} \Big) \times \underbrace{EF_p^e/CE}_{\text{constants}}$$

Thus, for the assumptions of this example, the entire methodology for estimating emission changes has been reduced to one equation involving:

- The rate of acceptance of solar systems (the parametric input)
- The building stock in the base year
- Several numerical constants.

This equation has been evaluated for the year 2000 for market acceptance rates of 10 percent, 20 percent, and 30 percent. (The percent of new buildings equipped with solar systems.) The results are summarized in Table 27 and Figures 11 and 12. The base year building count from which these forecasts were made was calculated from the nationwide building counts given in the GE Phase "O" report, allocated to the hypothetical city using the ratio of Baltimore's population to total U.S. population. For this reason the energy savings forecast should be considered as a representative estimate only. It can be seen from these data that the building types for which the largest potential fuel savings are projected due to solar heating and cooling systems use are (in descending order) heavy industrial, single-family houses, light industrial, retail malls, and auditoriums.

FIGURE 11
Potential Energy Savings in Hypothetical City
(Displacement of Electricity Only)

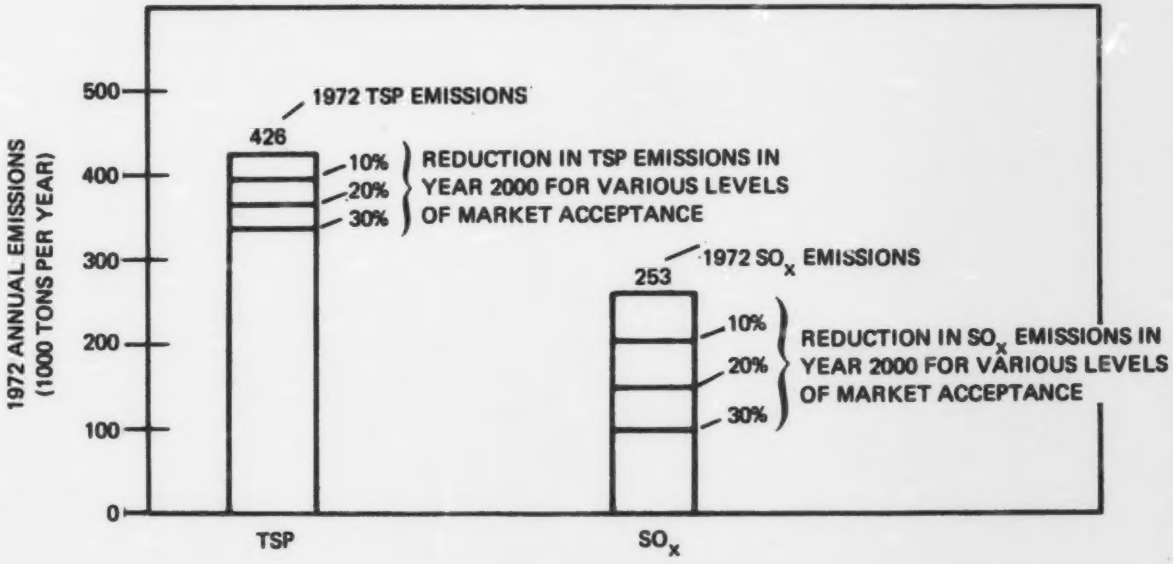


Notes:

1. All solar-induced fuel saving is electricity
2. Nationwide building stock* allocated to hypothetical city using Baltimore population
3. Constant rate of acceptance of solar systems: 30% of all new buildings
4. Energy savings by building type taken from Table 27

*From GE Phase 0 Report

FIGURE 12
Potential Power Plant Emission Savings in Hypothetical City in Year 2000 Resulting From Reduced Electrical Demand Due To Solar System Use



Notes:

1. 1972 emission levels: Baltimore SMSA areawide emissions, (EPA 1972 National Emissions Report)
2. All solar-induced savings will be electricity from coal
3. Coal sulfur content: 1%
4. Market acceptance is percent of new buildings equipped with solar heating/cooling systems
5. Areawide 25-year growth index: 1.2.

Table 27
Estimated Electricity Savings For Hypothetical City

Building Type (j)	Per-Building Energy Savings, 10^3 kWh/yr (Uj)	Base Year Building Stock (Nj (To))	Energy Savings (Year 2000), 10^6 kWh/yr, (10% Market Penetration)*
1	34.6	455,984	1,366
2	1,007	35	3
3	1,382	1,565	187
4	3,592	15	5
5	892	491	38
6	684	68	4
7	397	5,368	184
8	1,191	2,888	298
9	2,952	4,183	1,069
10	6,500	3,040	1,711
11	1,218	1,453	153
12	1,083	203	19
13	695	5,046	304
14	206	104	2
15	810	276	19
16	27,087	248	582
17	198	10,227	175
			6,121 x 10^6 kWh/yr

*Note:

- 10% market penetration: 6,121 million kWh/yr
- 20% market penetration: 12,242 million kWh/yr
- 30% market penetration: 18,363 million kWh/yr

* * * * *

The energy savings and air quality improvement in an urban area due to the use of solar heating and cooling systems will depend on several factors, especially the rate at which solar systems are utilized, the specific fuels which are displaced, and patterns of energy demand and supply for the area. The methodology described in this chapter is a mathematical model for estimating this improvement in air quality for any urban area. The model defines the relationships between potential fuel savings (U) and associated reduction in air pollution emissions (E):

$$E = f_1(N, G, S, F)$$

$$U = f_2(E)$$

based on:

- The current building stock in the area(N)
- The expected areawide growth index (G)
- Any postulated rate of solar system utilization (S)
- Estimates of the fuels which will be displaced by solar systems (F)

The sample application of the methodology indicates that under certain circumstances the use of solar systems will result in significant emission reductions for some urban areas. Since the majority of solar systems will be installed in new rather than existing buildings, and because electricity is used most often for space conditioning of new buildings, it is likely that the use of solar energy will displace coal and oil used to generate electricity. In this case, the air pollutants for which potential reductions would be most significant would be suspended particulates and sulfur oxides. Using actual building stock data for Baltimore, and a 25 year areawide growth index of 1.2, emission reductions of up to 2.4 percent for TSP and 7.3 percent for SO_x were estimated, assuming all fuel savings would be coal burned to produce electricity.

A key feature of the methodology is that it can be used for parametric analyses. This feature makes the methodology well suited to the evaluation of solar heating and cooling as a technological option for controlling air pollution.

It is recommended that the model be included in air quality forecasts for an AQMA where large scale use of solar heating and cooling systems are expected in order to assess in more detail the long range impacts on air quality.

Term	Definition
FFC_k	Fuel use factor (power plants)
FFN_{jkm}	Fuel use factor (end-use consumption)
$G(T_x)$	Growth index for a region for year T_x referenced to base year T_o
HE_{km}	Heating/cooling equipment efficiency
N_j	Total number of buildings of type j
NET_j	Number of solar retrofits in buildings of type j
NST_j	Number of new solar-equipped buildings of type j
$S_j(T)$	Percent of new buildings equipped with solar systems in year T
t	Time
T_o	Base year to which areawide growth is referenced
T_x	Year for which fuel savings are forecast
U_{jk}	Fuel savings
UT_k^c	Areawide fuel savings (commercial buildings)
UT_k^r	Areawide fuel savings (residential buildings)
UT_k^t	Areawide fuel savings (total)